e-Forum on High-Energy Nuclear Physics in China
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SINAP

AMPT model studies of heavy-ion collisions at RHIC and LHC

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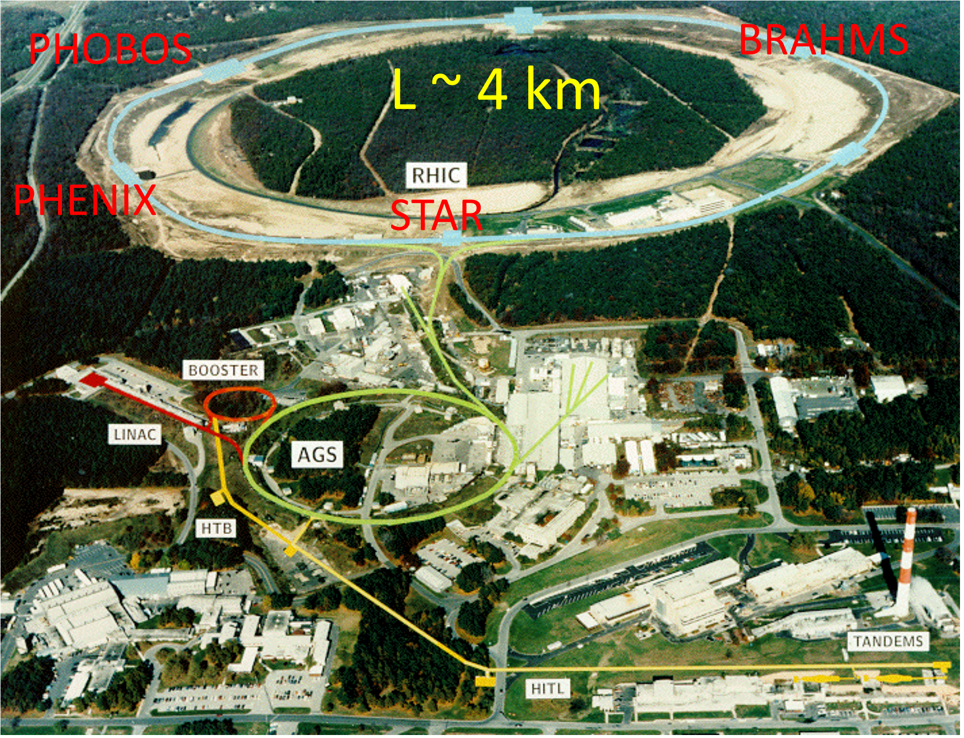
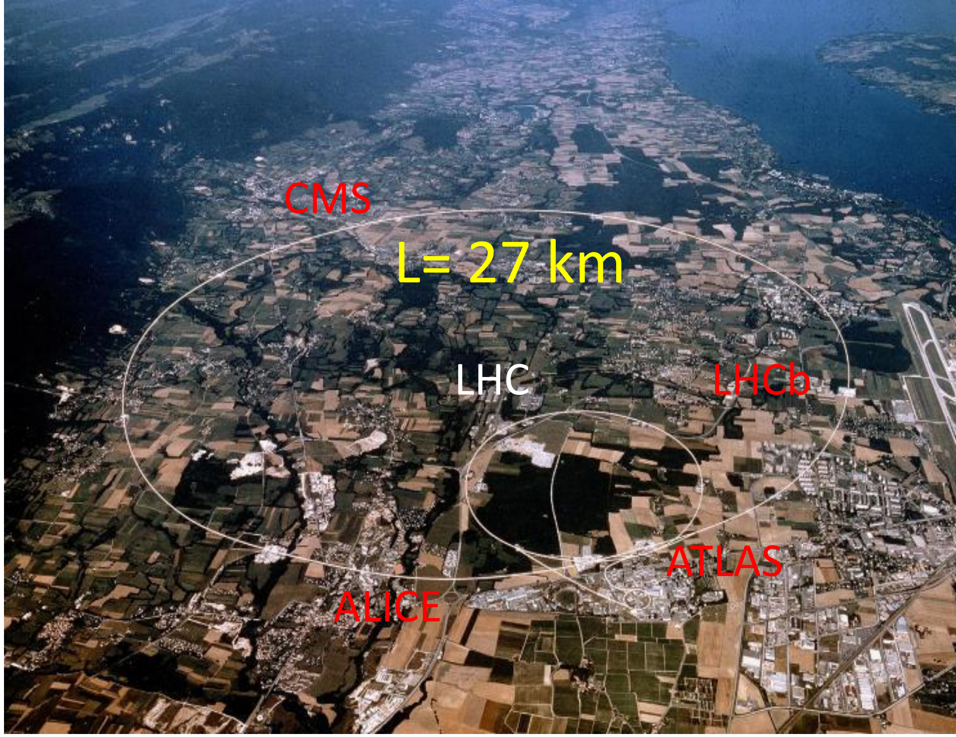
Outlines

- Introduction
- Initial fluctuations, higher-order anisotropic flows, and di-hadron correlation
- Multiplicity and harmonic flows fitting
- Specific shear viscosity of QGP
- v_2 splitting in the beam-energy scan program
- Work to be done in the near future





RHIC:

BNL, New York, USA

Au+Au@200GeV

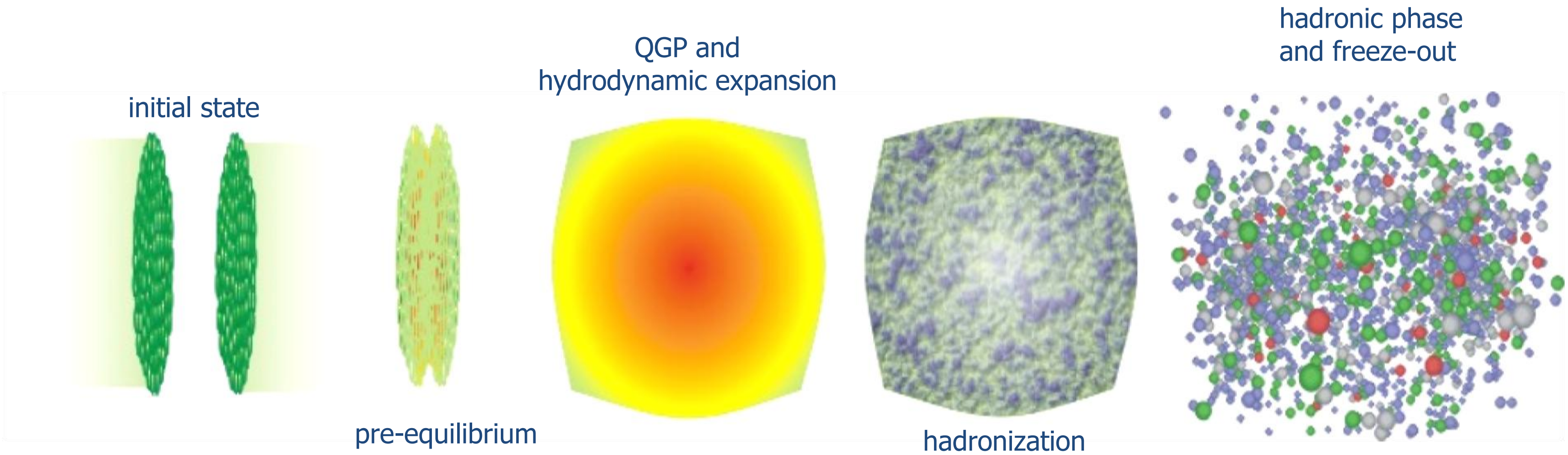
LHC:

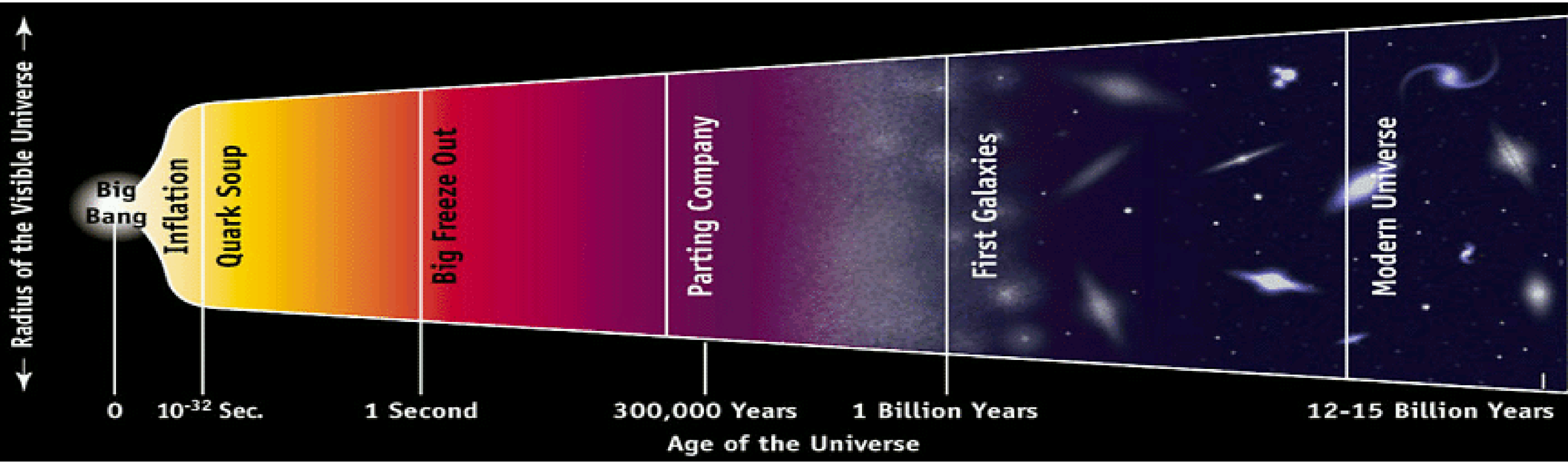
near Geneva, Switzerland, Europe

Pb+Pb@2.76TeV

ALICE@LHC
A Large Ion Collider Experiment

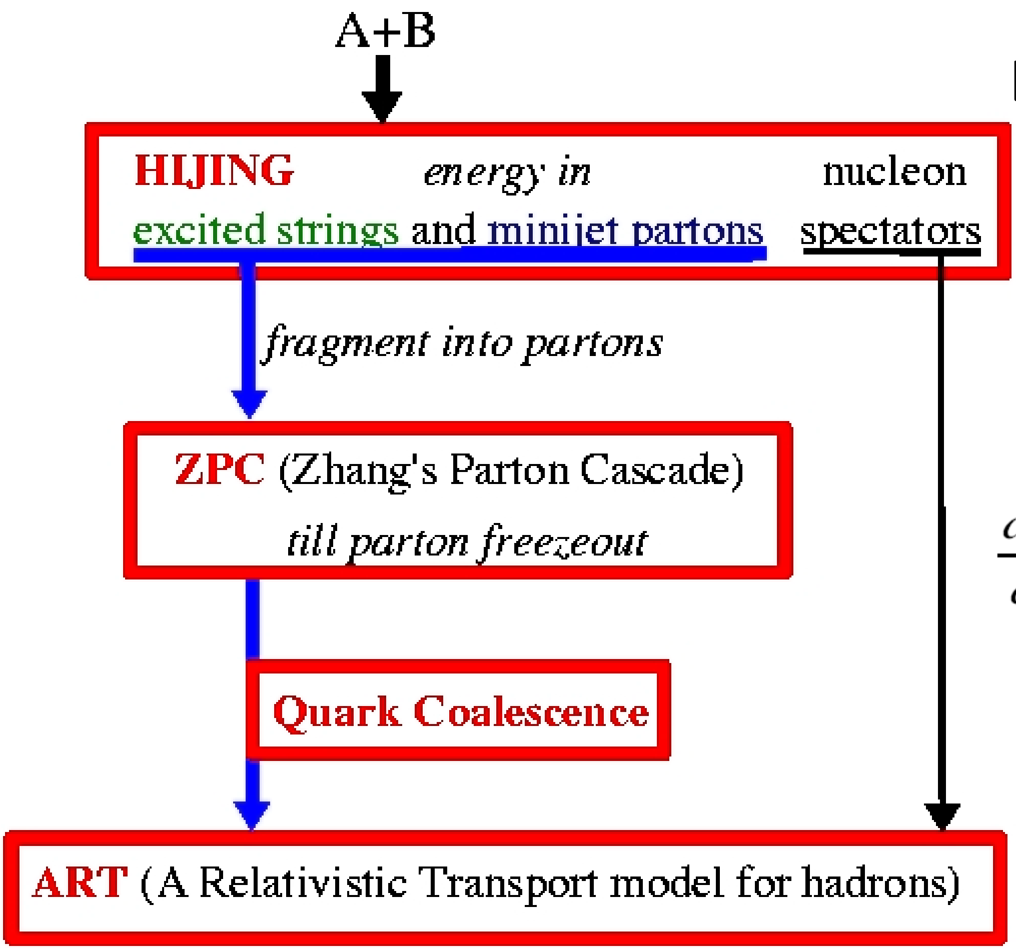
Little bang


initial state
pre-equilibrium
QGP and
hydrodynamic expansion
hadronization
hadronic phase
and freeze-out


Radius of the Visible Universe
Big Bang
Inflation
Quark Soup
Big Freeze Out
Parting Company
First Galaxies
Modern Universe
0
10^{-32} Sec.
1 Second
300,000 Years
1 Billion Years
12-15 Billion Years
Age of the Universe

A multiphase transport (AMPT) model with string melting

Structure of AMPT model with string melting



Lund string fragmentation function

$$f(z) \approx z^{-1}(1-z)^{a}\exp\left[-\frac{b(m^{2}+p_{t}^{2})}{z}\right]$$

z : light-cone momentum fraction

Parton scattering cross section

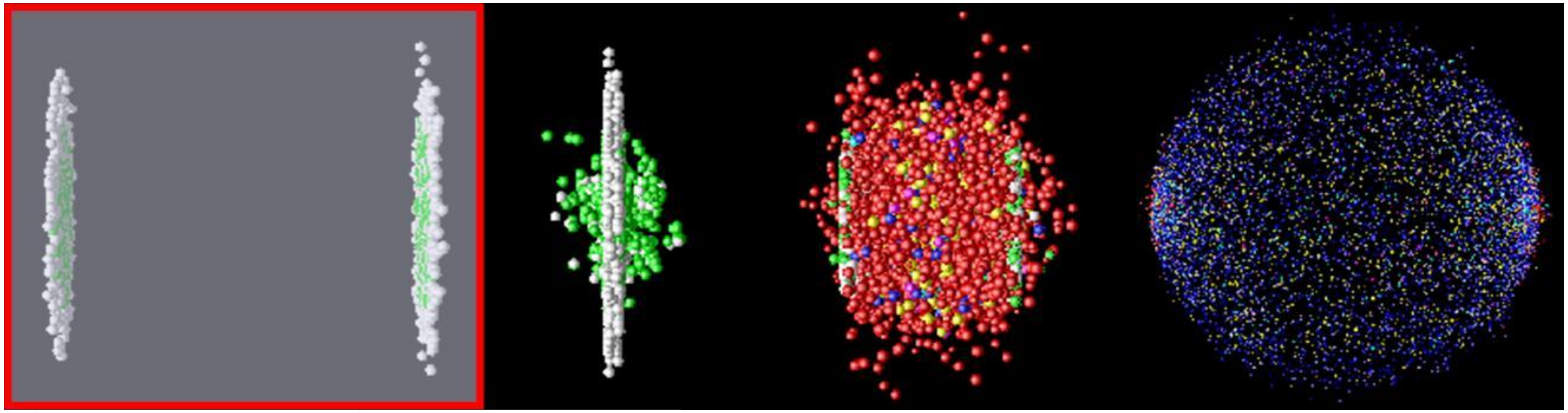
$$\frac{d\sigma}{dt} \approx \frac{9\pi\alpha^{2}}{2s^{2}}\left(1+\frac{\mu^{2}}{s}\right)\left(\frac{1}{t-\mu^{2}}\right)^{2}, \quad \sigma \approx \frac{9\pi\alpha^{2}}{2\mu^{2}}$$

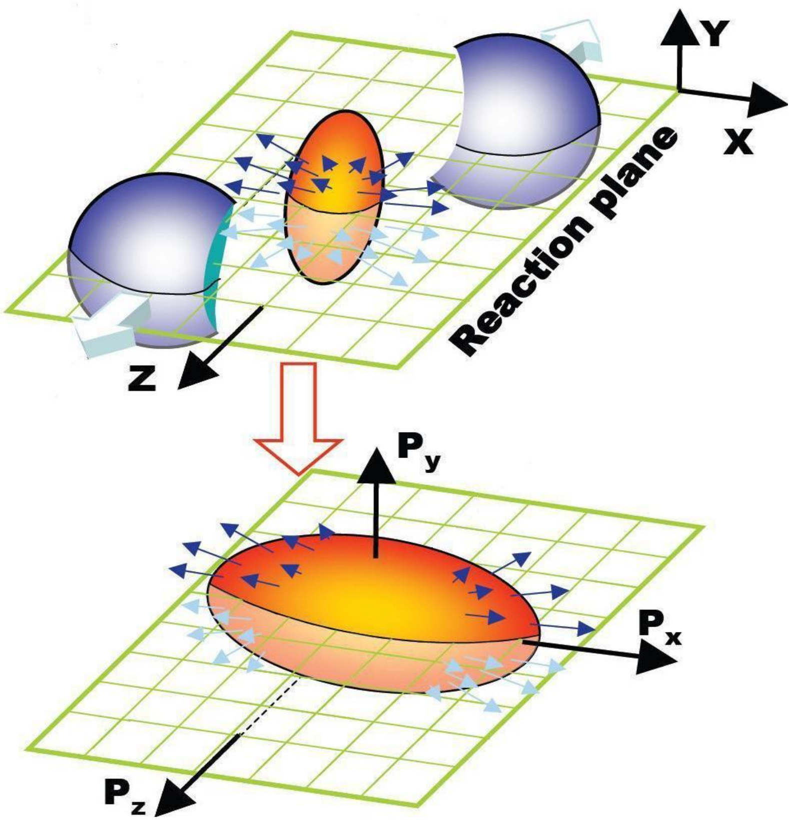
α: strong coupling constant

μ: screening mass

a, b: particle multiplicity

α, μ: partonic interaction



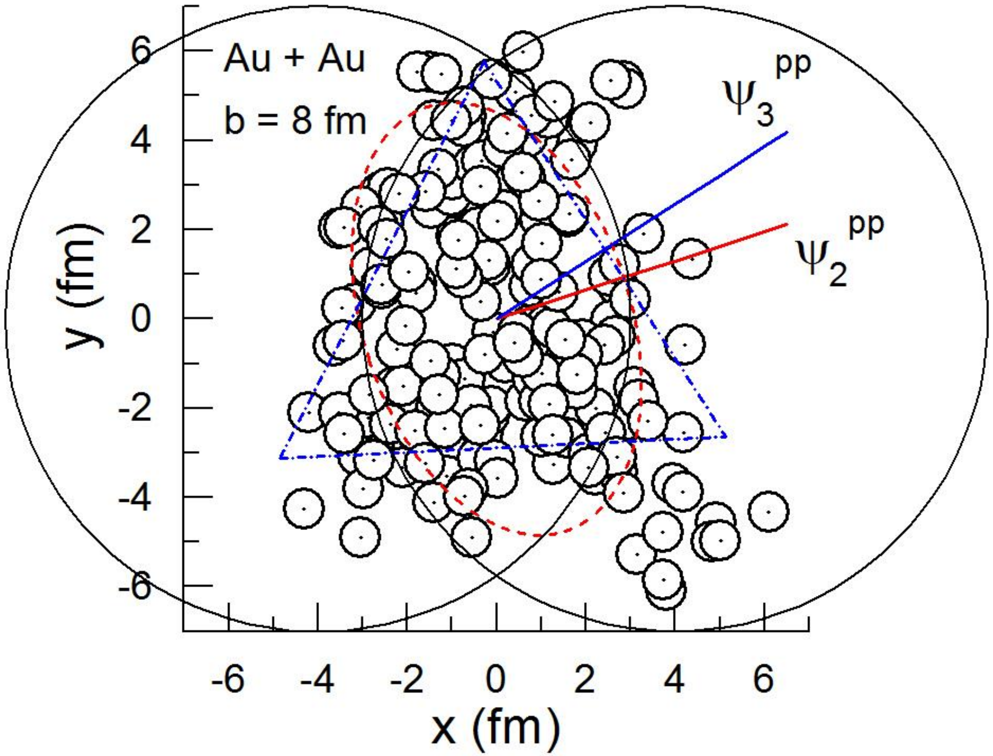


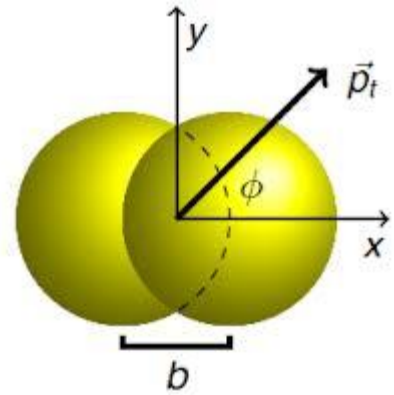
Eccentricity:

$$\varepsilon_2 = \frac{\left\langle y^2 - x^2 \right\rangle}{\left\langle y^2 + x^2 \right\rangle}$$

Elliptic flow:

$$v_2 = \frac{\left\langle p_x^2 - p_y^2 \right\rangle}{\left\langle p_x^2 + p_y^2 \right\rangle}$$

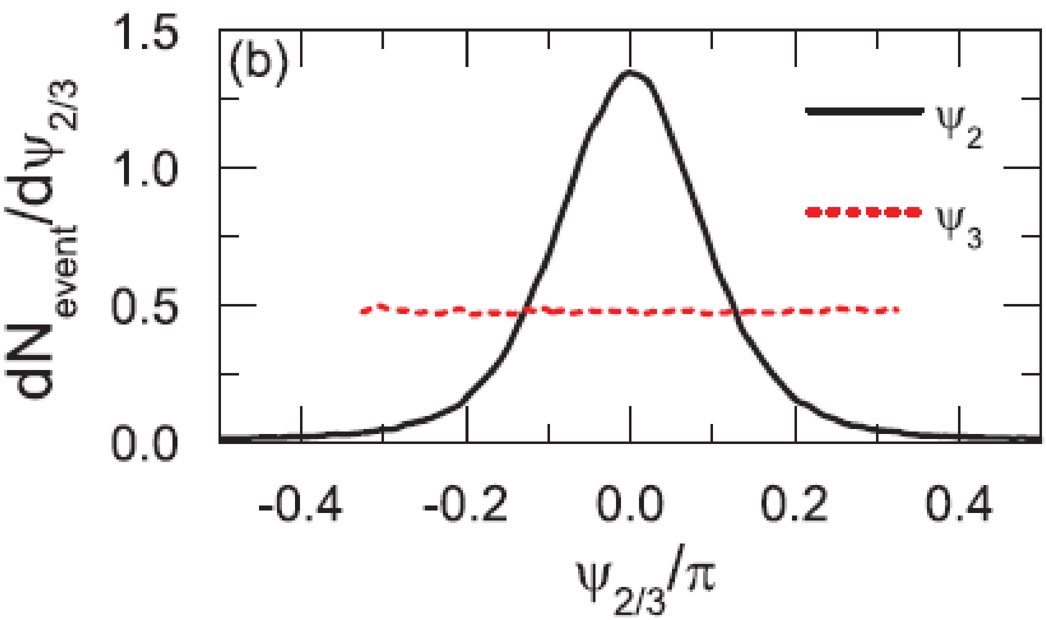




Transverse plane

Azimuthal angle

$$\Psi_n = \frac{1}{n}\tan^{-1}\frac{\langle \sin(n\phi)\rangle}{\langle \cos(n\phi)\rangle}$$



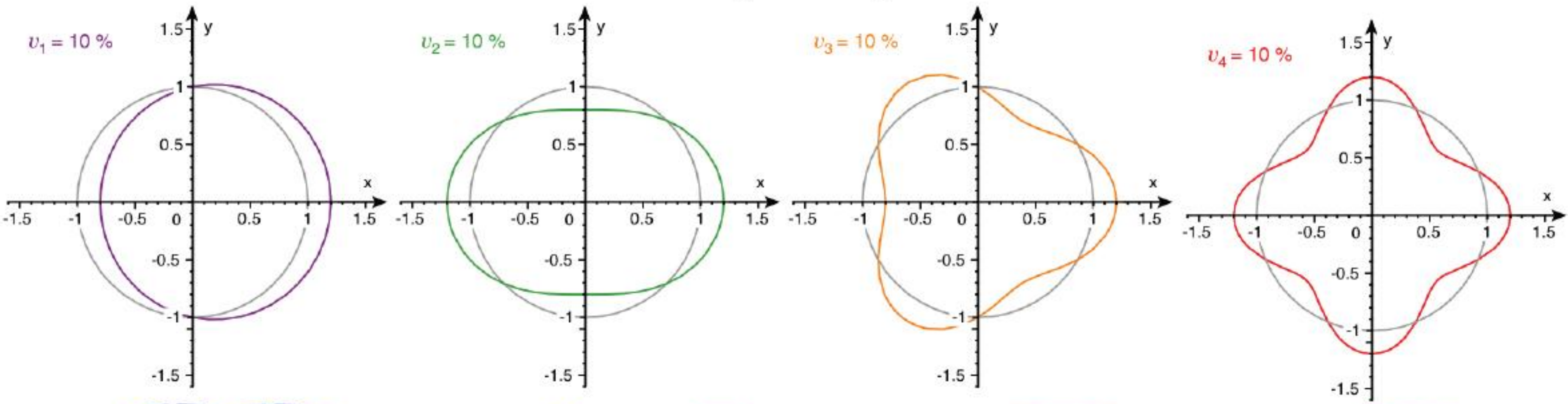
Ψ_2 no longer a δ function peaks at zero

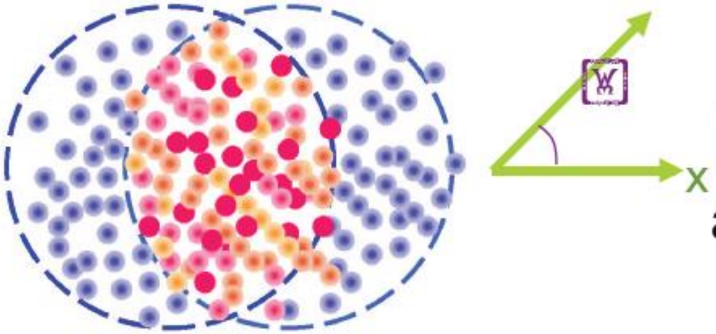
Ψ_3 totally from initial fluctuation uniformly distributed

Ψ_2 and Ψ_3 are independent of each other

Anisotropic flow

$$\frac{dN}{dp_T d\phi} = \frac{dN}{2\pi dp_T}\left[1+\sum_{n=1}^{\infty} 2v_n(p_T)\cos(n(\phi-\Psi_n))\right]$$





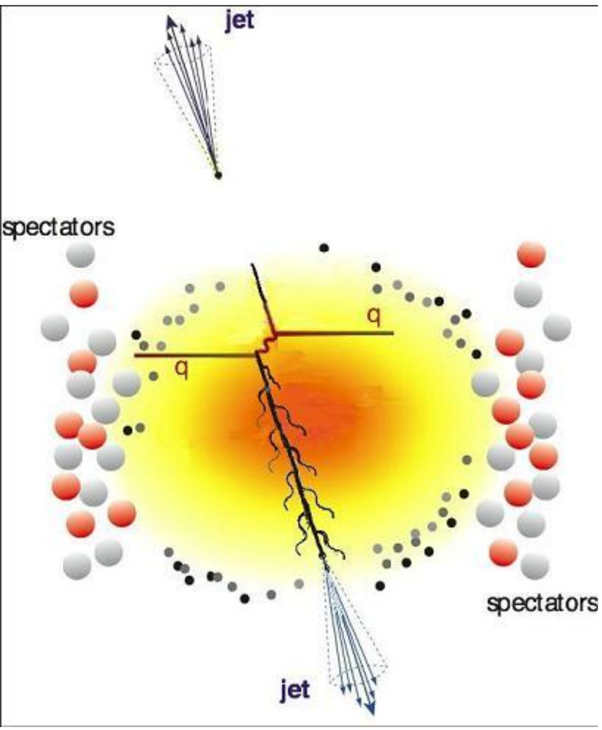
ε_n

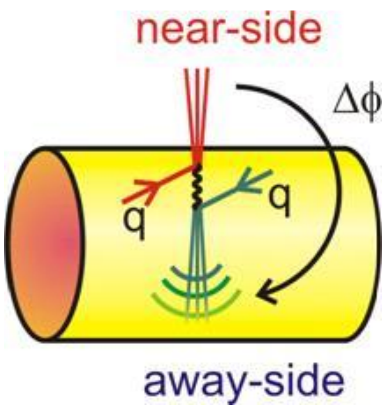
Interaction

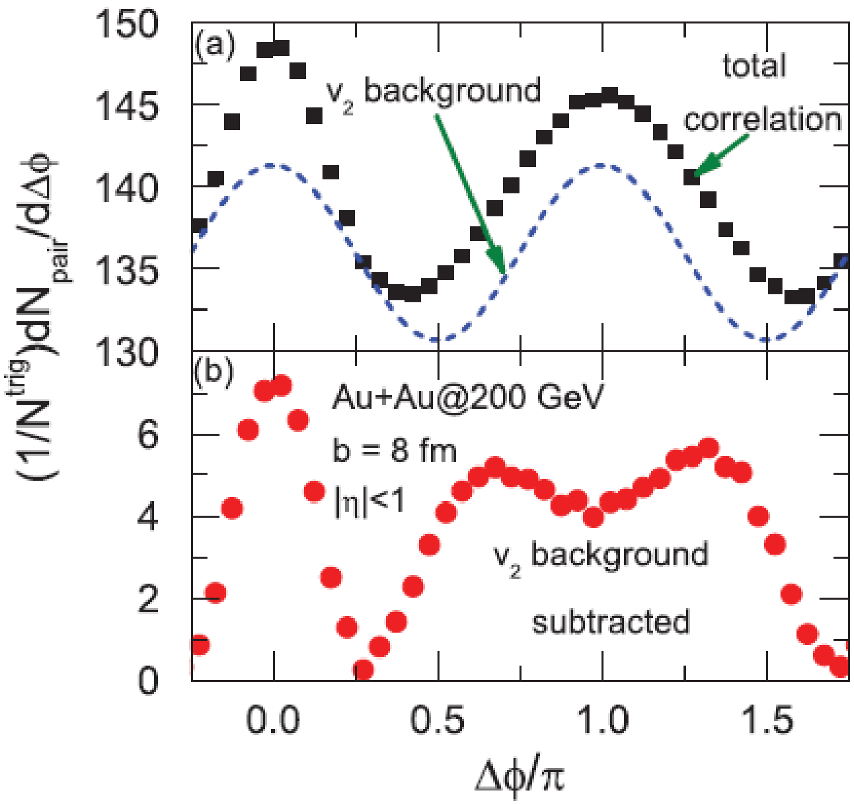
$\eta/s \sim v_n/\varepsilon_n$

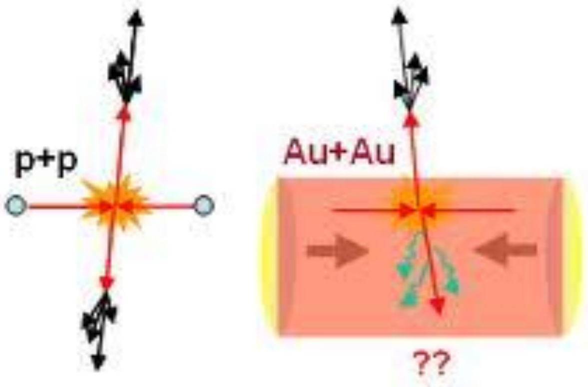
v_n

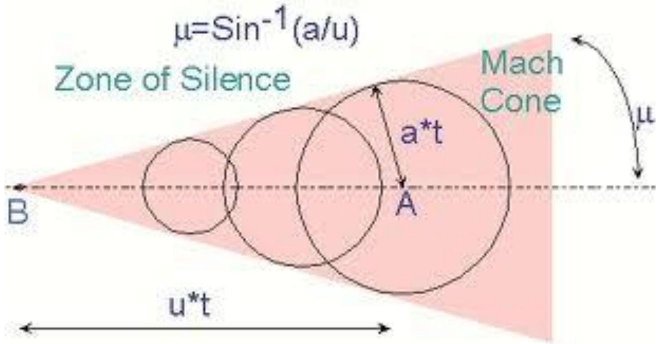
Jet and di-hadron correlation



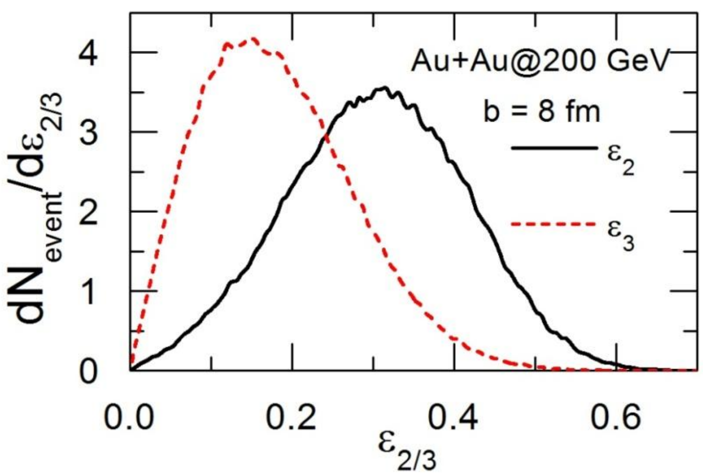


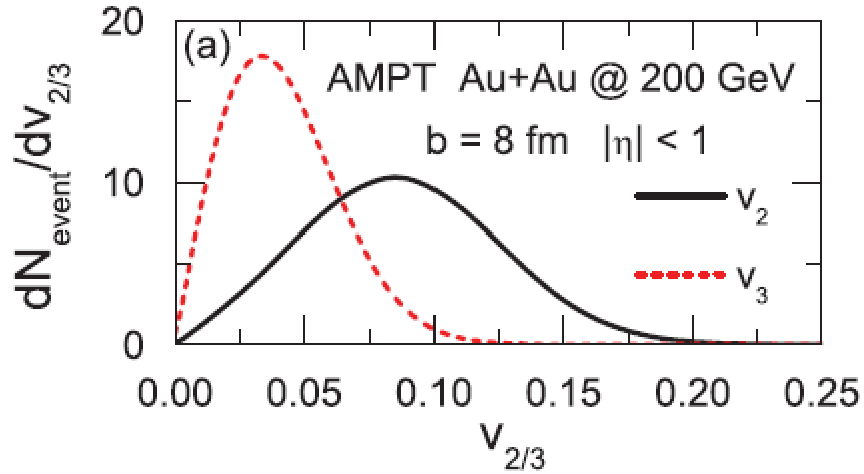


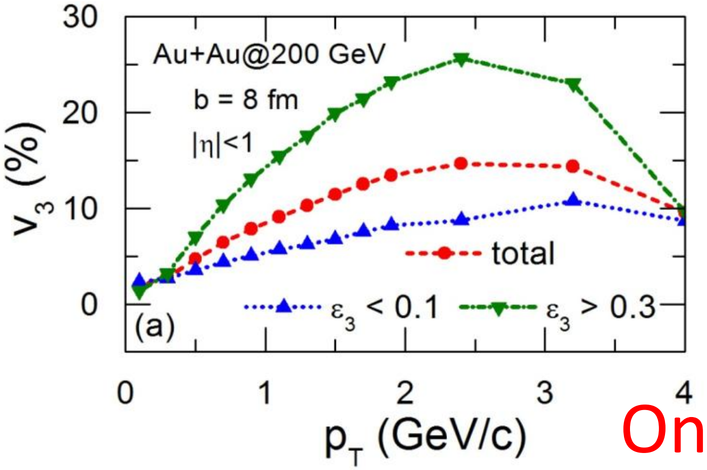


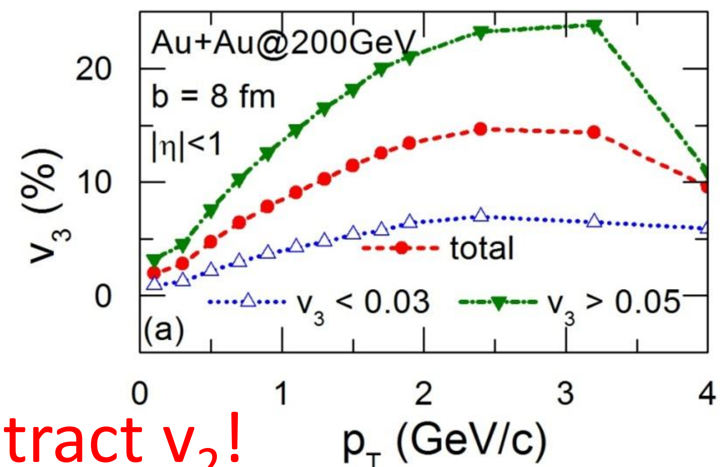


Mach cone?

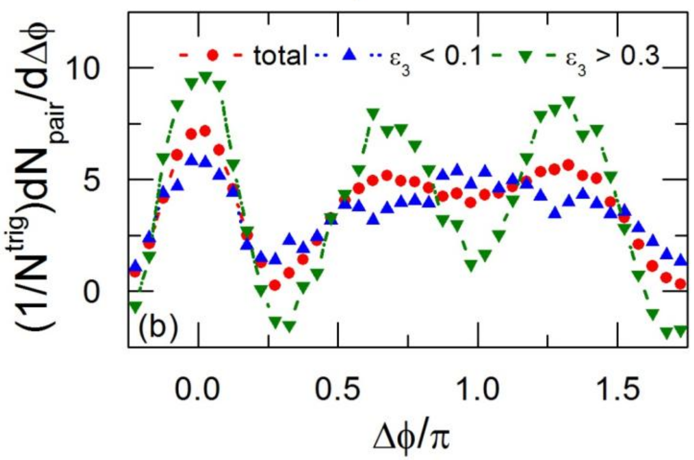


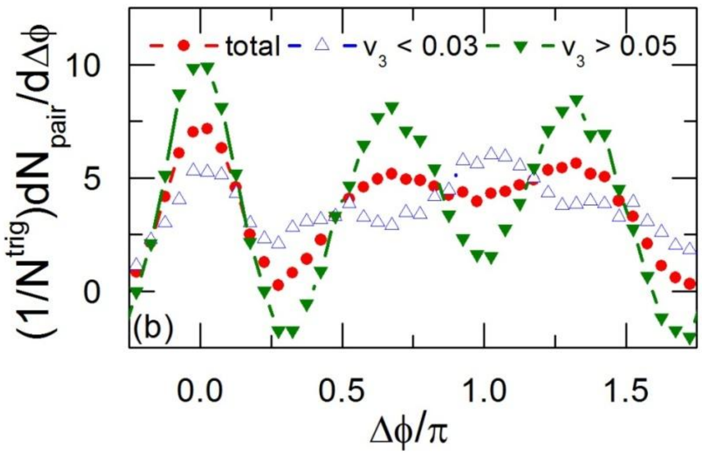






Only subtract v_2!





Single-particle azimuthal angular distribution:

$$f(p_T,\phi)=\frac{N(p_T)}{2\pi}\left[1+\sum_{n=1}^{\infty}2v_n(p_T)\cos(n(\phi-\Psi_n))\right]$$

Total correlation: $< \ >_e$ average over all events

$$\frac{dN_{pair}}{d\Delta\phi}=\left\langle\int f^{trig}(\phi)f^{assoc}(\phi+\Delta\phi)d\phi\right\rangle_e$$

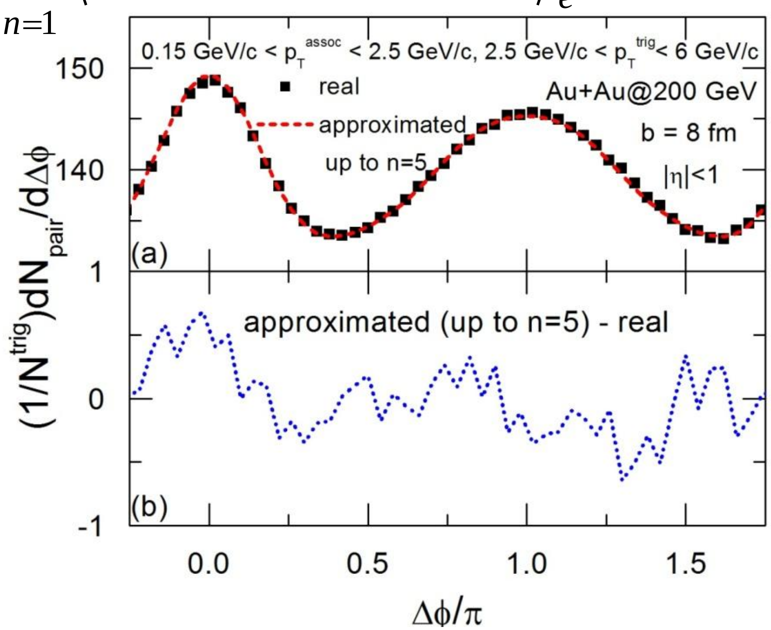
$$=\frac{1}{2\pi}\left[\left\langle N^{trig}N^{assoc}\right\rangle_e+2\sum_{n=1}^{\infty}\left\langle N^{trig}v_n^{trig}N^{assoc}v_n^{assoc}\right\rangle_e\cos(n\Delta\phi)\right]$$

real:

counting all possible pairs

approximated:

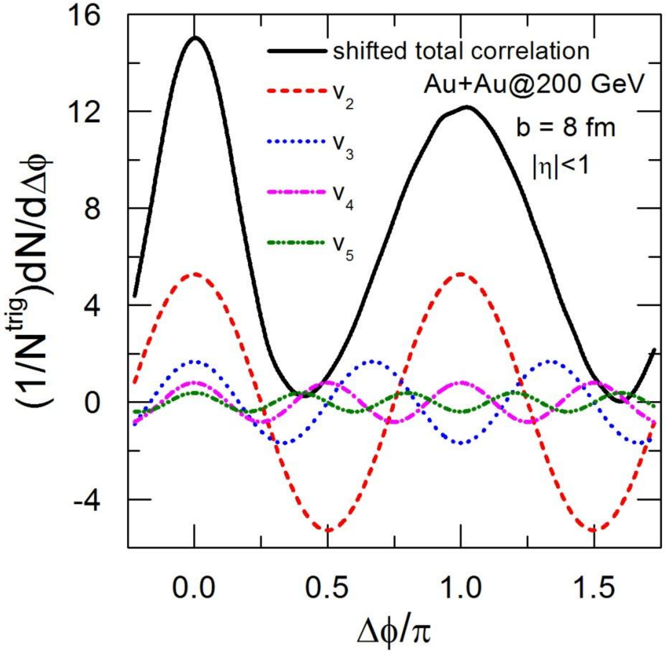
using above formula

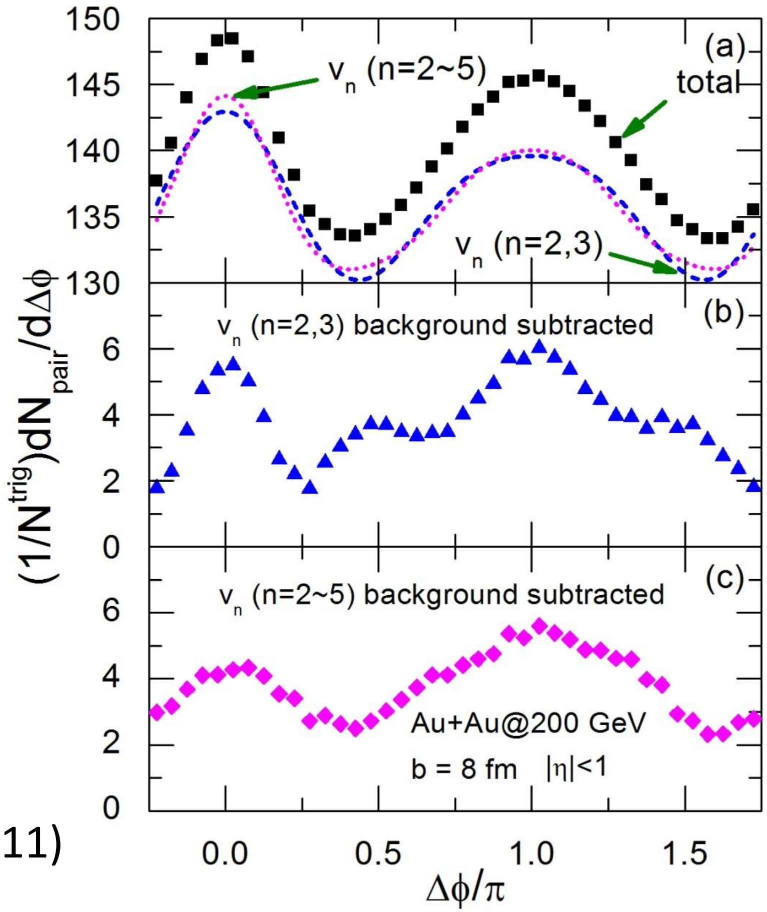


Background correlation:

$$\left(\frac{dN_{pair}}{d\Delta\phi}\right)_{back} = \frac{1}{2\pi}\left[\left\langle N^{trig}\right\rangle_e \left\langle N^{assoc}\right\rangle_e + 2\sum_{n=1}^{\infty}\left\langle N^{trig} v_n^{trig}\right\rangle_e \left\langle N^{assoc} v_n^{assoc}\right\rangle_e \cos(n\Delta\phi)\right]$$

$$= \frac{\left\langle N^{trig}\right\rangle_e \left\langle N^{assoc}\right\rangle_e}{2\pi}\left[1 + 2\sum_{n=1}^{\infty}\boxed{\frac{\left\langle N^{trig} v_n^{trig}\right\rangle_e}{\left\langle N^{trig}\right\rangle_e}}\,\boxed{\frac{\left\langle N^{assoc} v_n^{assoc}\right\rangle_e}{\left\langle N^{assoc}\right\rangle_e}}\cos(n\Delta\phi)\right]$$





Higher-order anisotropic flows should also be subtracted.

J. Xu and C. M. Ko, Phys. Rev. C 83, 021903(R) (2011)

Two-dimensional di-hadron correlation:

$$f(p_T,\phi,\eta) = \frac{N(p_T,\eta)}{2\pi}\left\{1 + 2\sum_n v_n(p_T,\eta)\cos[n(\phi-\Psi_n)]\right\}$$

$$\frac{d^2N_{\rm pair}^{\rm same}}{d\Delta\eta\, d\Delta\phi} = \frac{1}{\eta_{\max}-\eta_{\min}}\int_{\eta_{\min}}^{\eta_{\max}} d\eta \frac{1}{2\pi}\int_0^{2\pi} d\phi\, f(p_T^a,\phi,\eta) f(p_T^b,\phi+\Delta\phi,\eta+\Delta\eta)$$

$$= \frac{1}{\eta_{\max}-\eta_{\min}}\int_{\eta_{\min}}^{\eta_{\max}} d\eta \frac{N(p_T^a,\eta)N(p_T^b,\eta+\Delta\eta)}{(2\pi)^2}\left[1 + 2\sum_n v_n(p_T^a,\eta)v_n(p_T^b,\eta+\Delta\eta)\cos(n\Delta\phi)\right]$$

$$\left\langle\frac{d^2N_{\rm pair}^{\rm same}}{d\Delta\eta\, d\Delta\phi}\right\rangle_e \approx \frac{1}{\eta_{\max}-\eta_{\min}}\int_{\eta_{\min}}^{\eta_{\max}} d\eta \left\langle\frac{N(p_T^a,\eta)N(p_T^b,\eta+\Delta\eta)}{(2\pi)^2}\right\rangle_e$$

$$\times\left[1 + 2\sum_n \langle v_n(p_T^a,\eta)v_n(p_T^b,\eta+\Delta\eta)\rangle_e \cos(n\Delta\phi)\right]$$

Weak η dependence of v_n

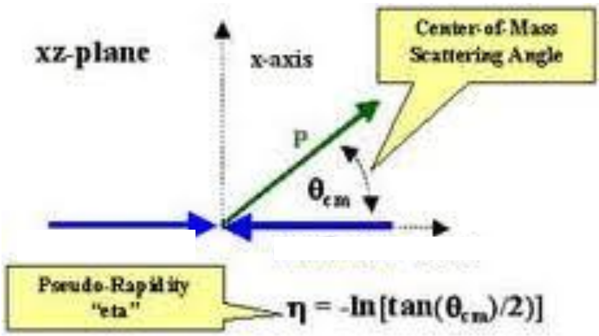
$$\langle v_n(p_T^a,\eta)v_n(p_T^b,\eta+\Delta\eta)\rangle_e \cos(n\Delta\phi)$$

$$\approx \langle v_n(p_T^a)\rangle_e \langle v_n(p_T^b)\rangle_e \cos(n\Delta\phi)$$

$$+\,\mathrm{FF}[v_n(p_T^a), v_n(p_T^b)]\cos(n\Delta\phi) + \mathrm{NF}(\Delta\phi,\Delta\eta)$$

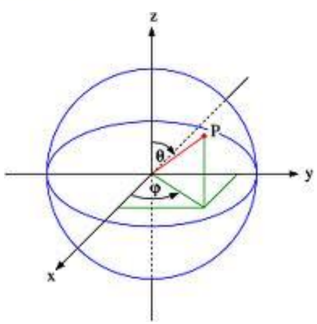
FF: flow fluctuation

NF: non-flow

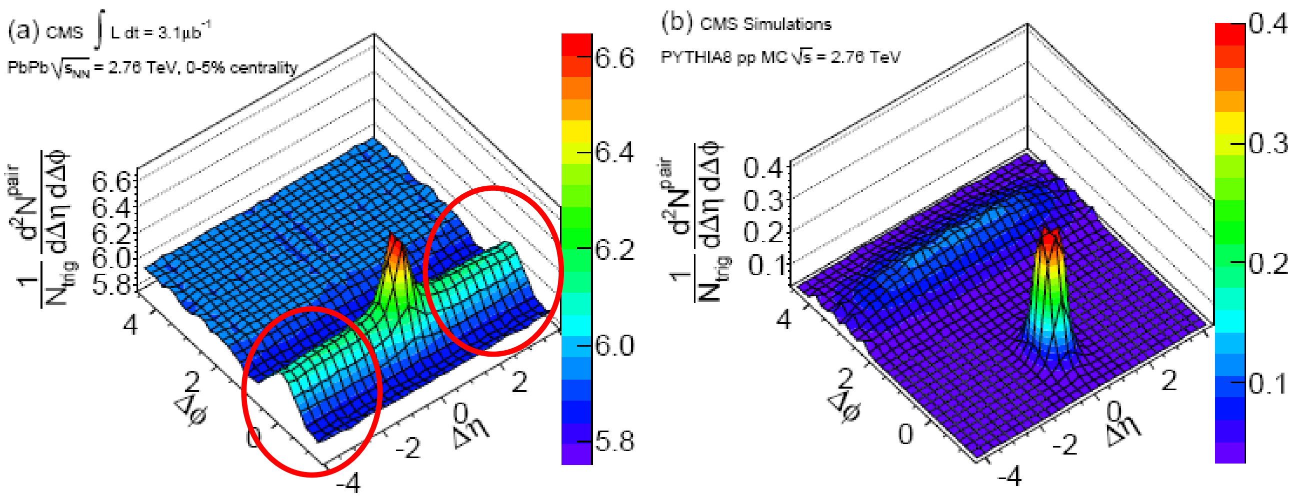


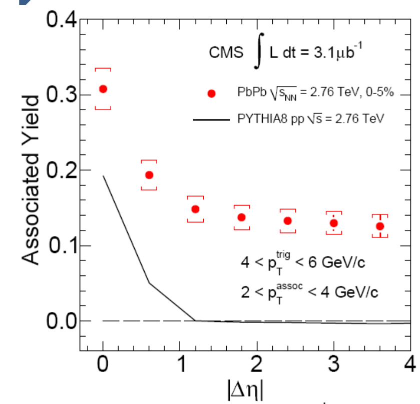
$$\left\langle\frac{d^2N_{\rm pair}^{\rm mix}}{d\Delta\eta\, d\Delta\phi}\right\rangle_e = \frac{1}{\eta_{\max}-\eta_{\min}}\int_{\eta_{\min}}^{\eta_{\max}} d\eta \left\langle\frac{N(p_T^a,\eta)N(p_T^b,\eta+\Delta\eta)}{(2\pi)^2}\right\rangle_e$$

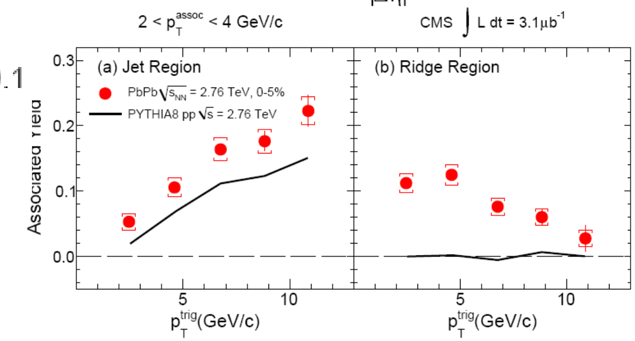
$$\left\langle\frac{d^2N_{\rm pair}^{\rm same}}{d\Delta\eta\, d\Delta\phi}\right\rangle_e \Big/ \left\langle\frac{d^2N_{\rm pair}^{\rm mix}}{d\Delta\eta\, d\Delta\phi}\right\rangle_e$$ = raw/background = signal



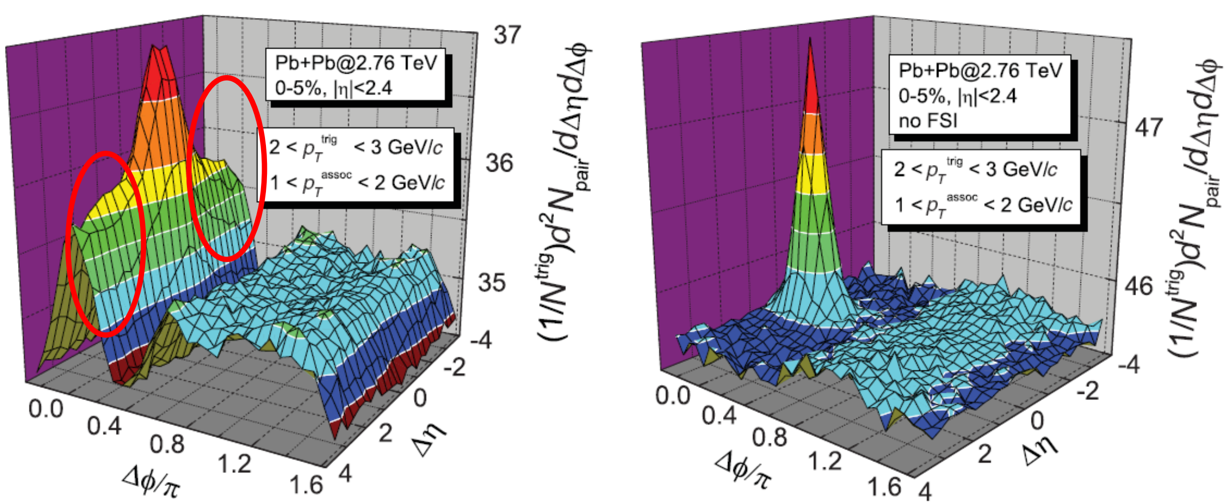
Initial fluctuation → Higher-order anisotropic flow → ridge

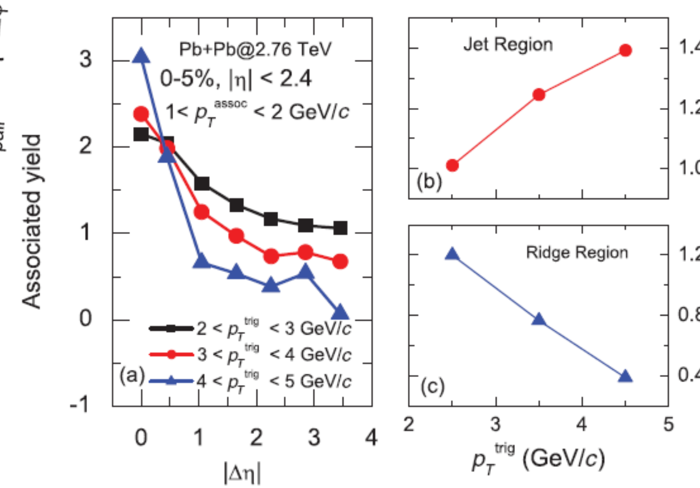






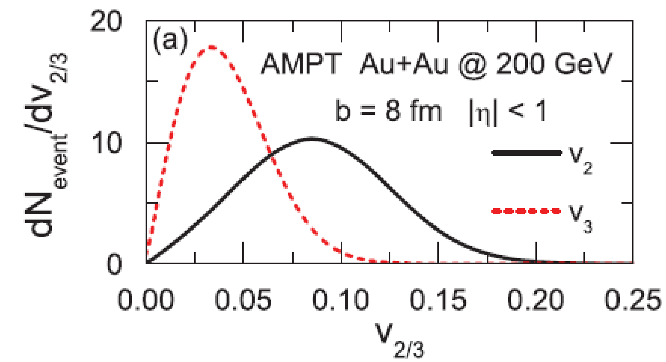
CMS Collaboration, JHEP (2011)





J. Xu and C. M. Ko, Phys. Rev. C 84 044907 (2011)

Flow, non-flow, and flow fluctuation



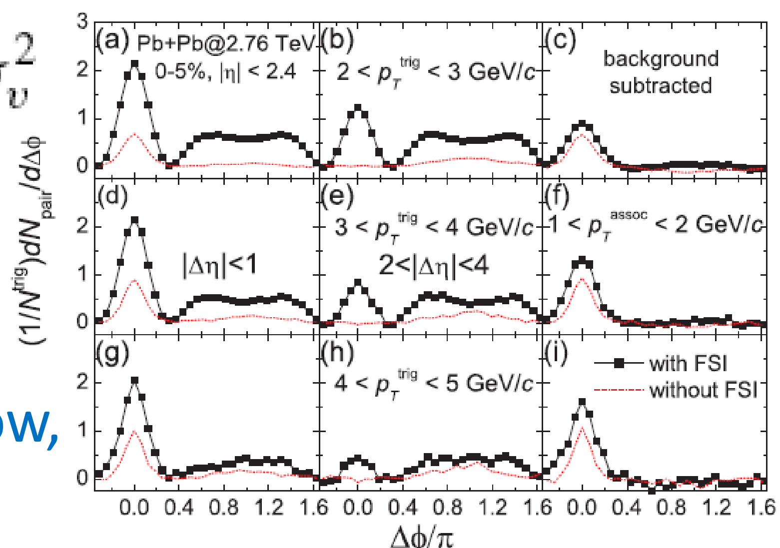
- Flow v: collective behavior
- Flow fluctuation $\sigma_v^2 \equiv \langle v^2 \rangle - \langle v \rangle^2$
- Non-flow δ: jet, resonance decay, only small Δη

$$v\{2\} \equiv \sqrt{\langle \cos(\phi_1 - \phi_2) \rangle} \quad v\{\mathrm{EP}\} \equiv \frac{\langle \cos(\phi - \Psi_R) \rangle}{R}$$

$$v\{4\} \equiv \left(2\langle \cos(\phi_1 - \phi_2) \rangle^2 - \langle \cos(\phi_1 + \phi_2 - \phi_3 - \phi_4) \rangle\right)^{1/4}$$

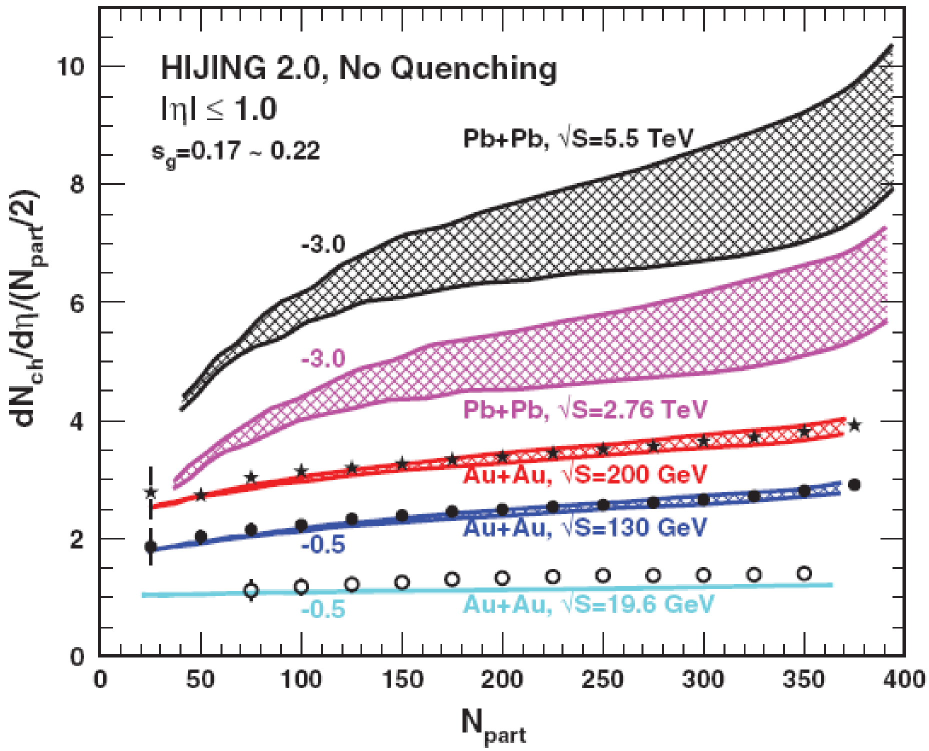
$$v\{2\}^2 = \langle v \rangle^2 + \delta + \sigma_v^2 \quad v\{4\}^2 = \langle v \rangle^2 - \sigma_v^2$$

$$v\{\mathrm{EP}\}^2 = \langle v \rangle^2 + \left[1 - \frac{(I_0 - I_1)}{(I_0 + I_1)} \left(\chi^2 - \chi_s^2 + \frac{2i_1^2}{(i_0^2 - i_1^2)}\right)\right] \times \delta + \left[1 - \frac{2(I_0 - I_1)}{I_0 + I_1} \left(\chi^2 - \chi_s^2 + \frac{2i_1^2}{i_0^2 - i_1^2}\right)\right] \sigma_v^2$$

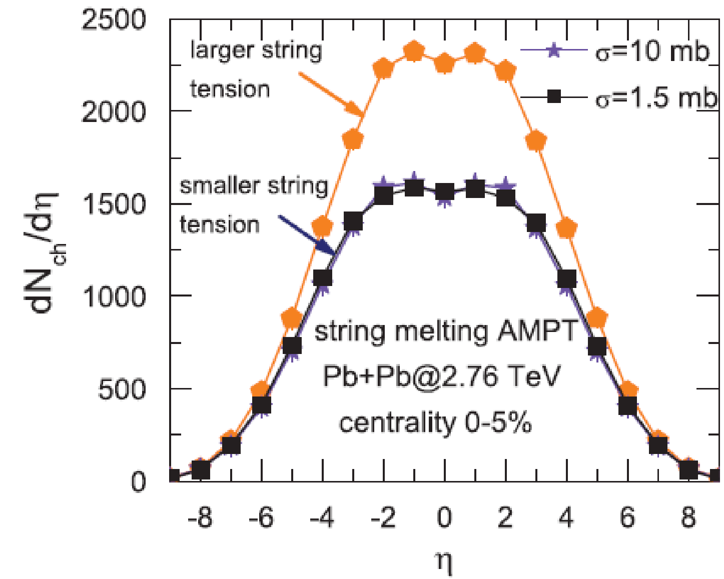


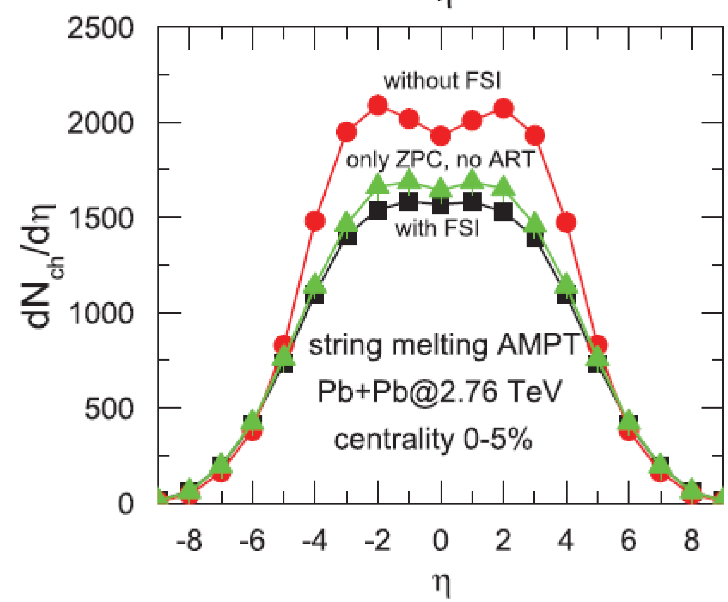
It's still an open question to disentangle flow, non-flow, and flow fluctuation accurately!

Reconfiguration of AMPT



W. T. Deng *et al.*, PRC (2011)

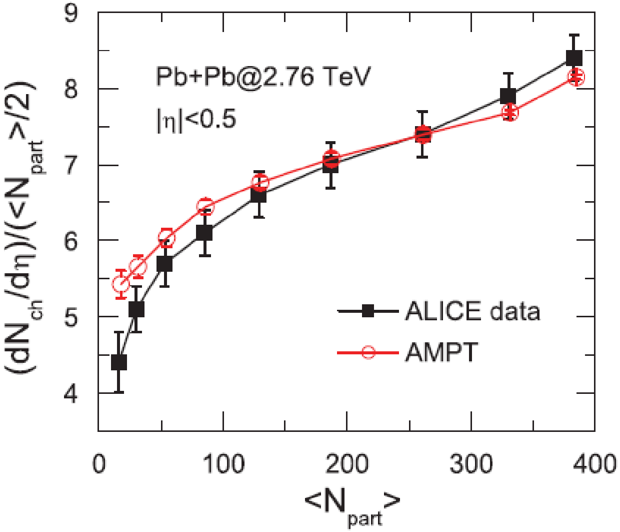


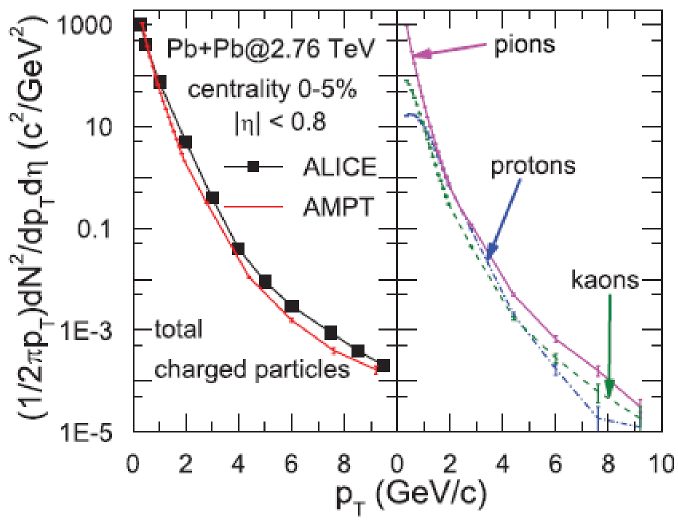


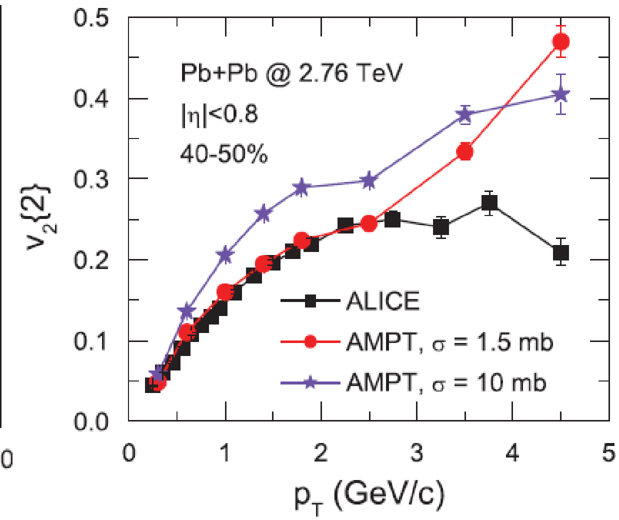
Final state interaction (FSI) reduces the multiplicity by 25% due to the longitudinal work!

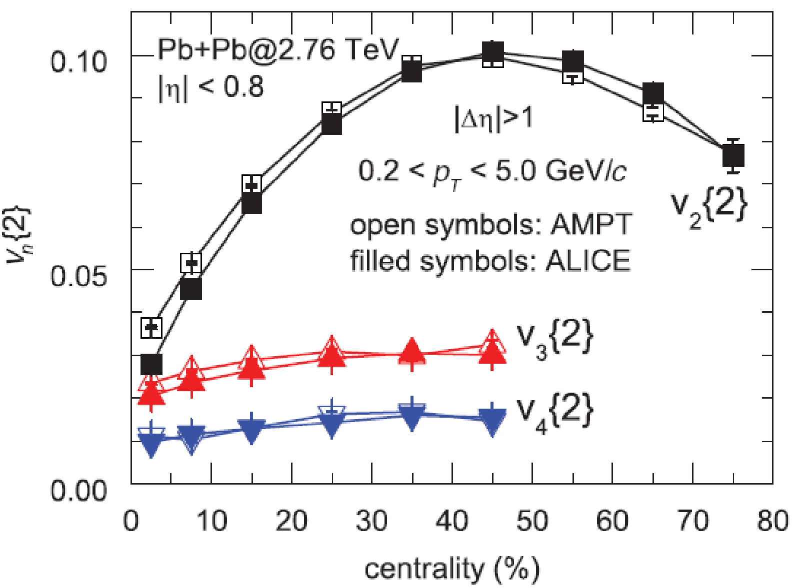
J. Xu and C. M. Ko, Phys. Rev. C 83, 034904 (2011)

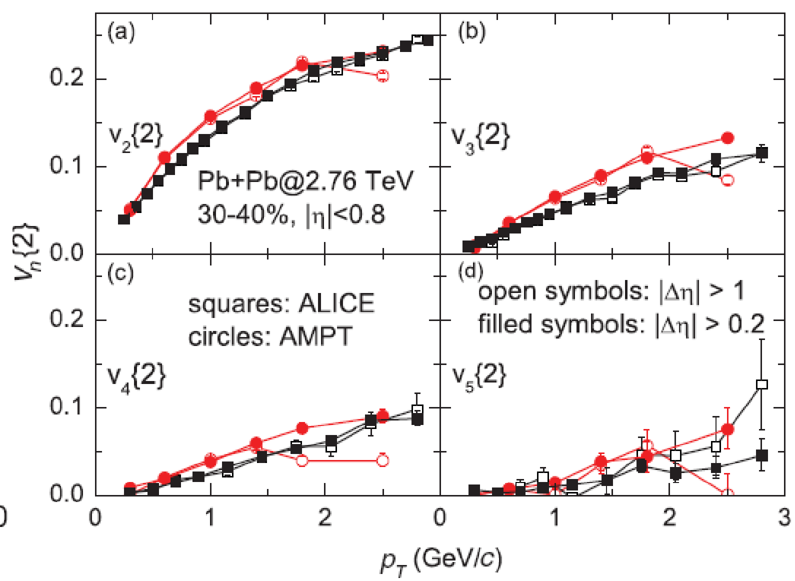
Reconfiguration at LHC







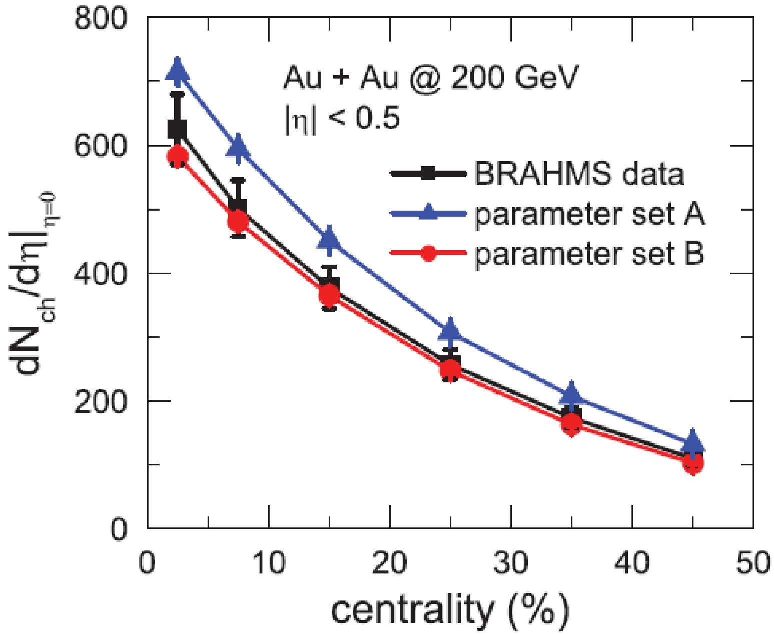


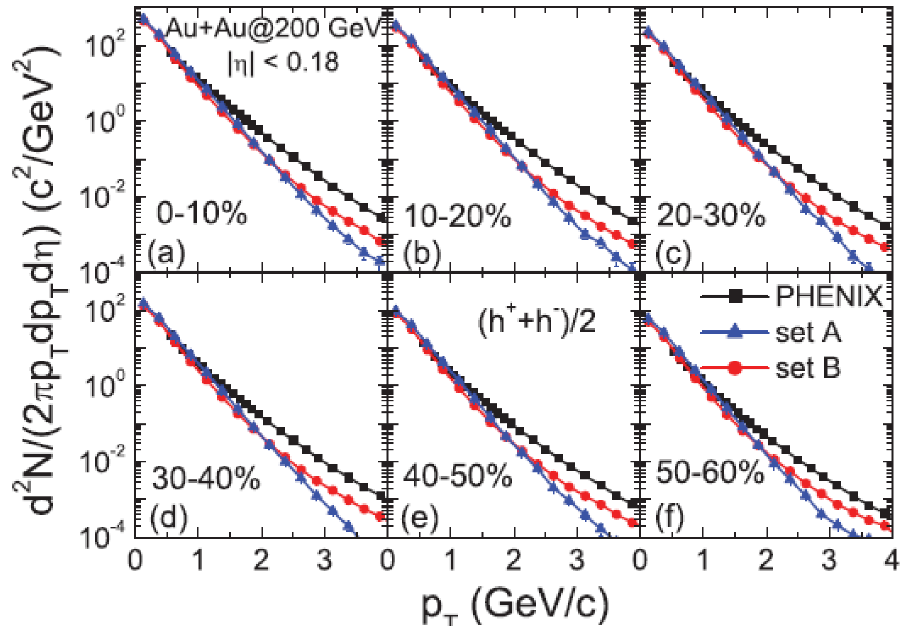


J. Xu and C. M. Ko, Phys. Rev. C 83, 034904 (2011); 84, 044907 (2011)

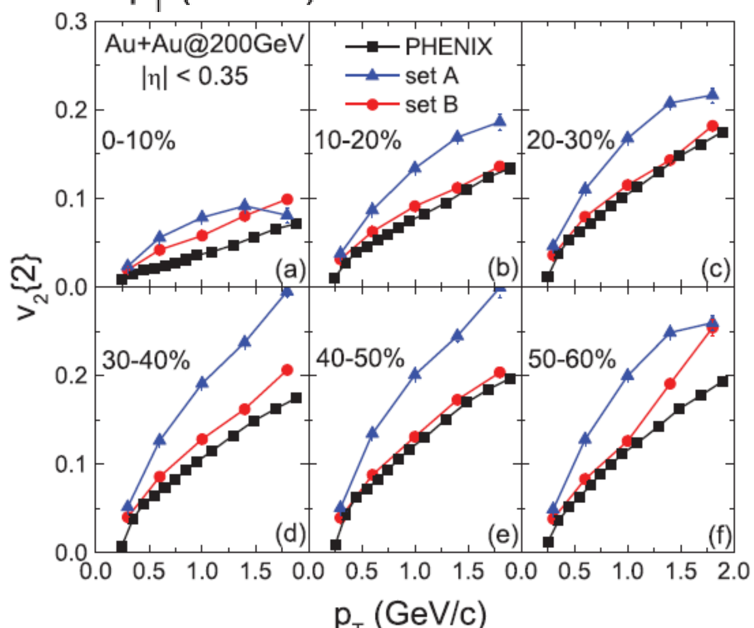
Once v_2 is fitted, higher-order flows are automatically fitted.

Reconfiguration at RHIC



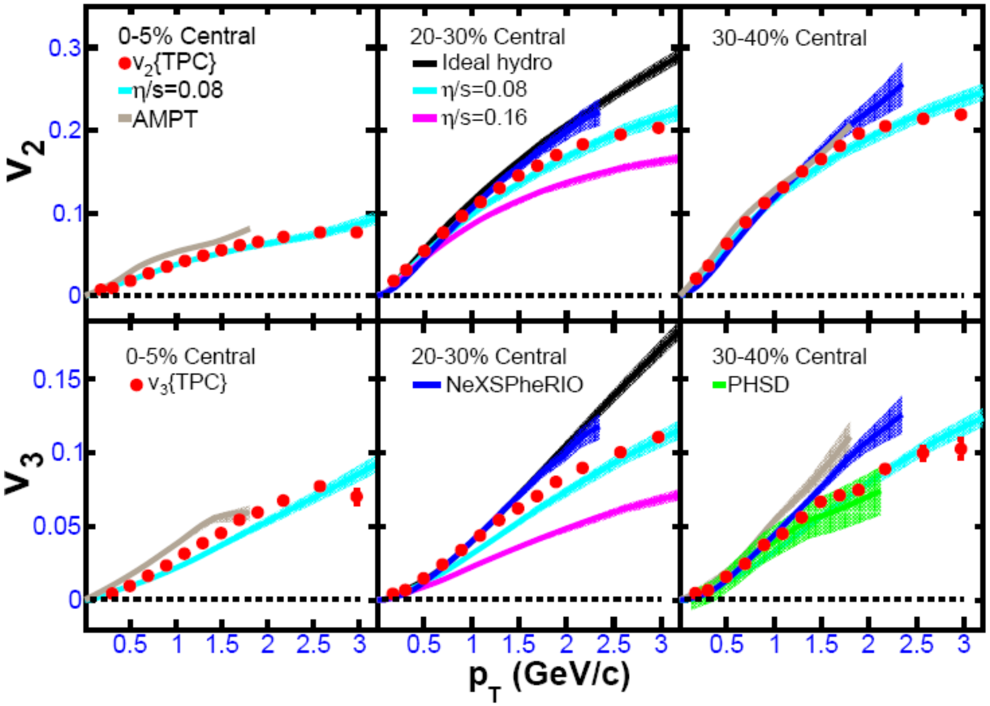


	a	b (GeV^{-2})	α_s	μ (fm^{-1})
A	2.2	0.5	0.47	1.8
B	0.5	0.9	0.33	3.2

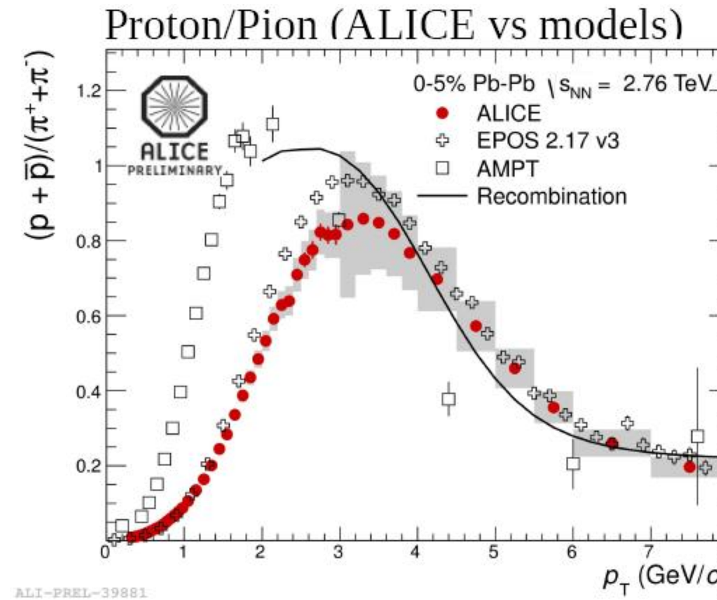


Same parameterization
for both LHC and RHIC.

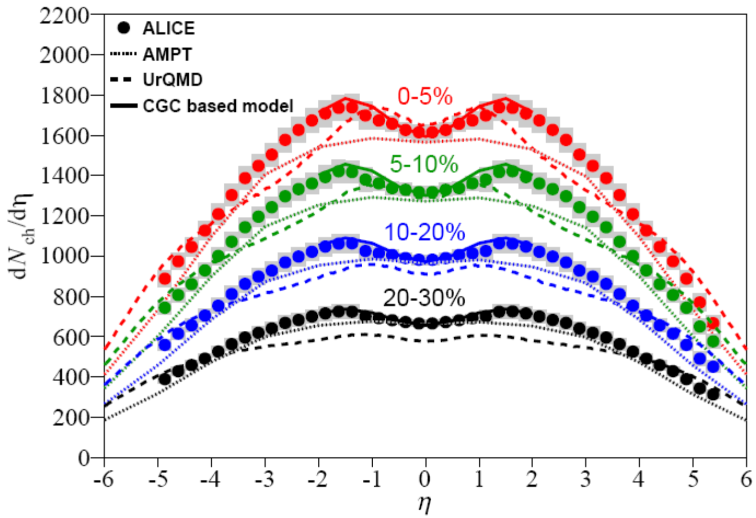
J. Xu and C. M. Ko, Phys. Rev. C 84, 014903 (2011)



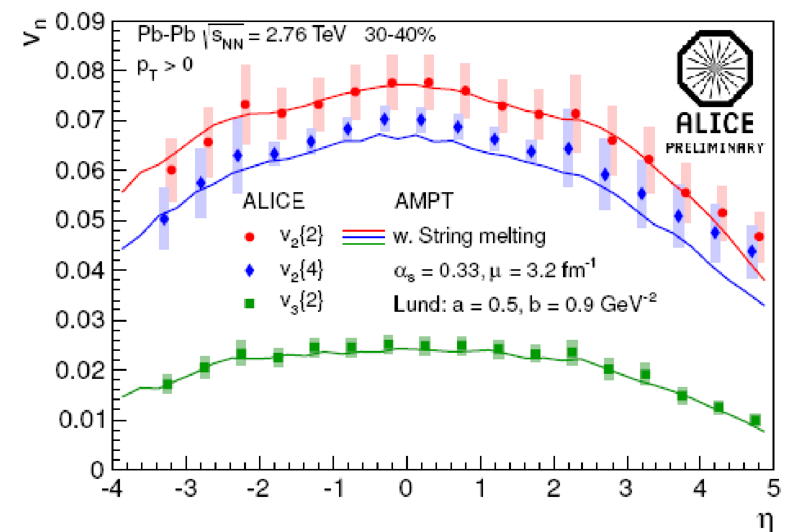
STAR Collaboration, arXiv: 1301.2187 [nucl-ex]



ALICE Collaboration talk at QM2012

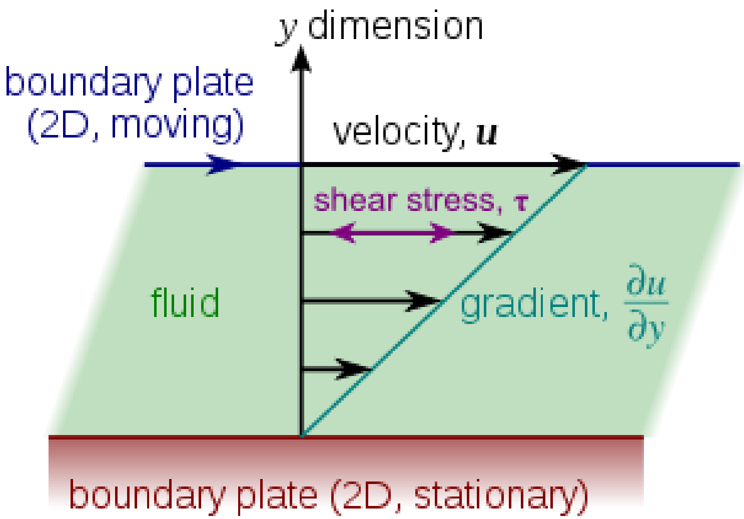


ALICE Collaboration, arXiv: 1304.0347 [nucl-ex]



ALICE Collaboration, arXiv: 1302.0894 [nucl-ex]

Shear viscosity



$$\tau = \frac{F}{A} = \eta \frac{\partial u}{\partial y}$$

$$\eta \propto \frac{\langle p \rangle}{\sigma}$$

Strong interaction → Small η

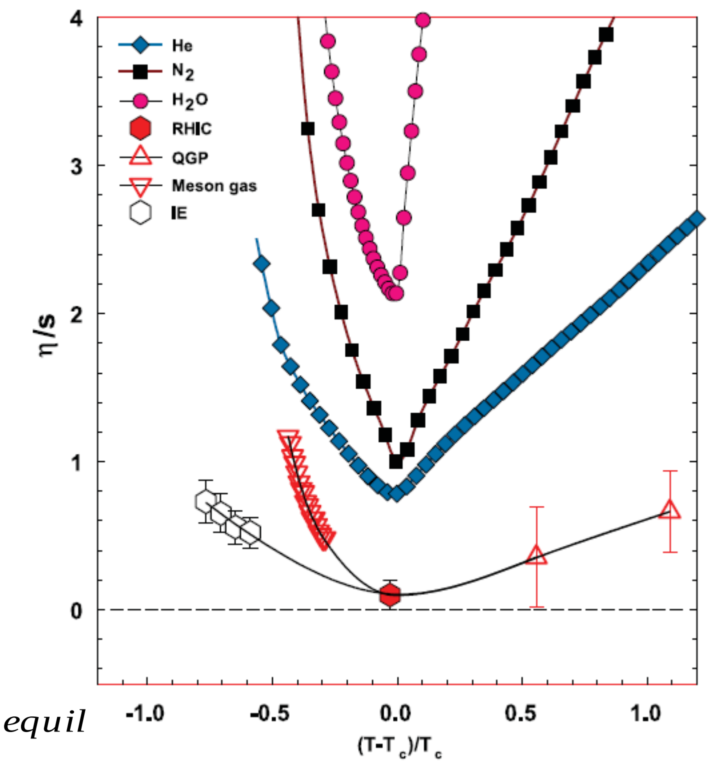
Viscous hydrodynamics: $\frac{\eta}{s}$

Ideal fluid: $\eta = 0$

Ads/CFT: $\frac{\eta}{s} \geq \frac{1}{4\pi}$

Green-Kubo's formula:

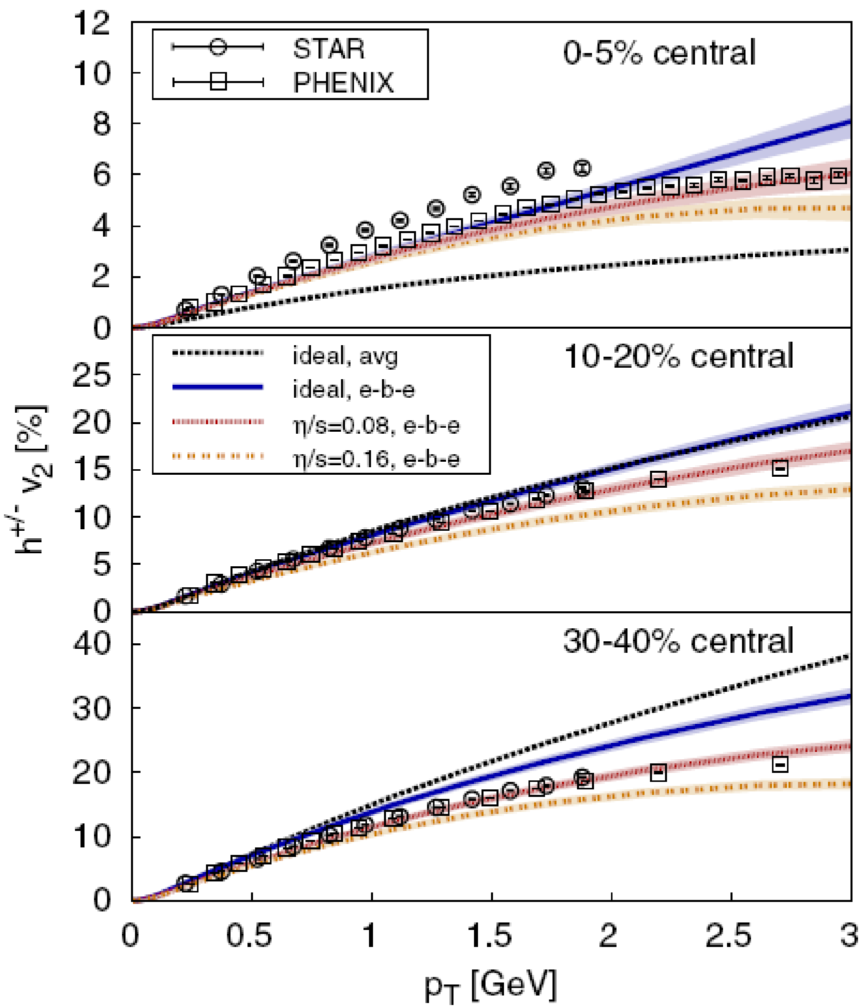
$$\eta = \frac{1}{T}\int d^3r \int_0^\infty dt \left\langle \pi^{ij}\left(\vec{0},0\right)\pi^{ij}\left(\vec{r},t\right)\right\rangle_{equil}$$

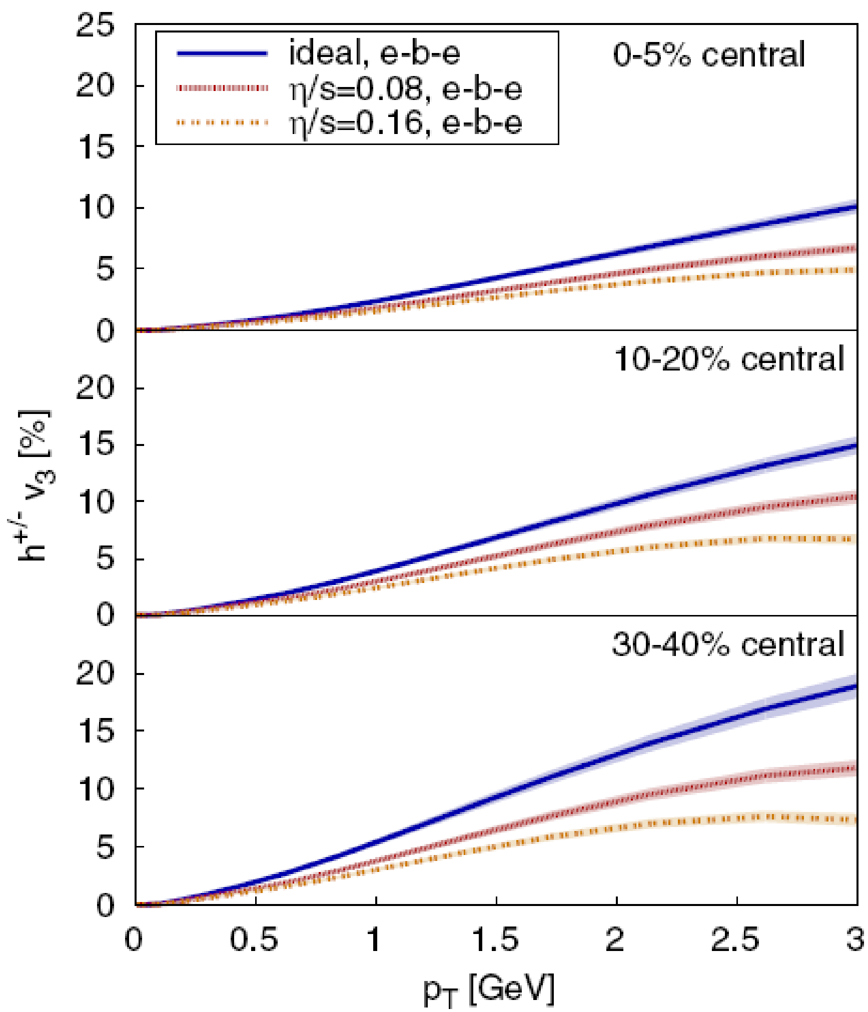


Lacey *et al.*, PRL (2007).

Extract $\frac{\eta}{s}$ of QGP!

shear viscosity and anisotropic flow

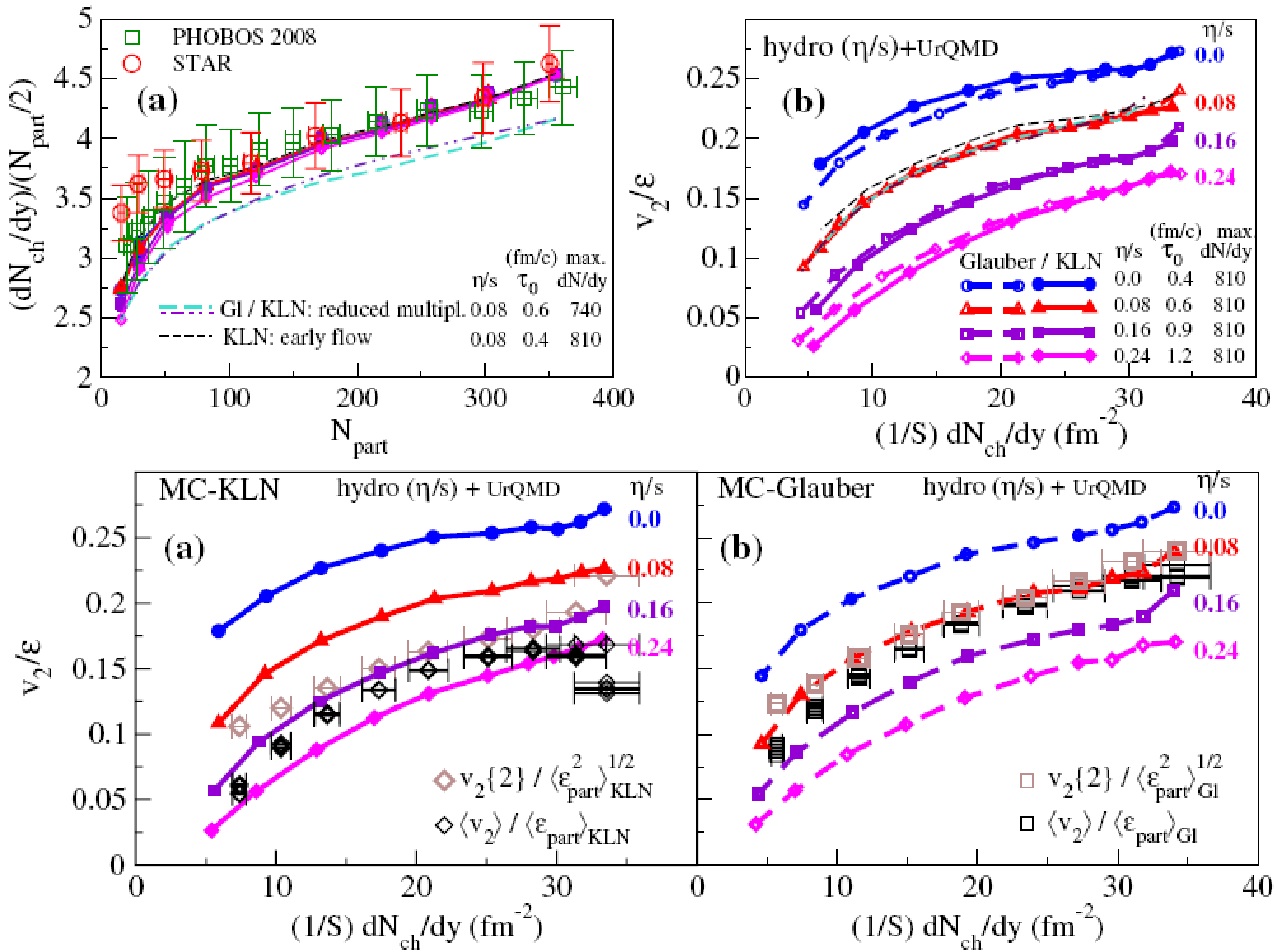




Higher-order anisotropic flows are more sensitive to the shear viscosity.

B. Schenke *et al.*, PRL (2010)

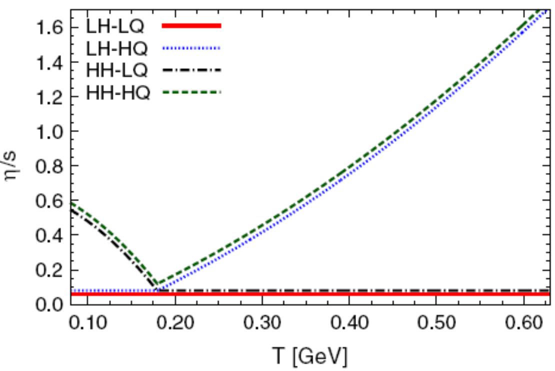
QGP: a nearly ideal fluid



$$1 < 4\pi(\eta/s)_{QGP} < 2.5$$

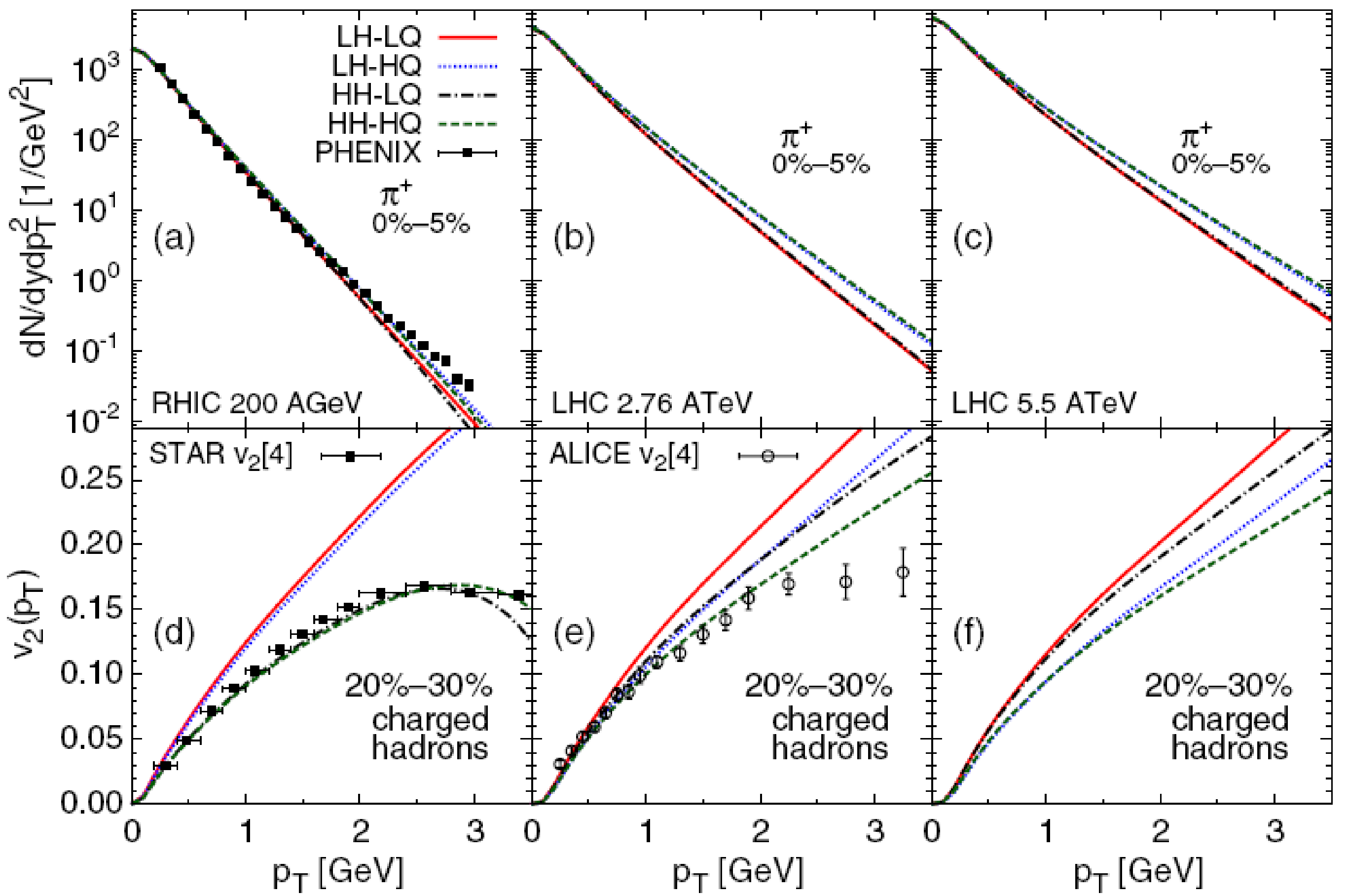
H. C. Song, *et al.*, PRL (2011)

Influence of a temperature-dependent shear viscosity



RHIC v_2: more sensitive to hadronic η/s

LHC v_2: more sensitive to partonic η/s



H. Niemi *et al.*, PRL (2011)

Shear viscosity from AMPT

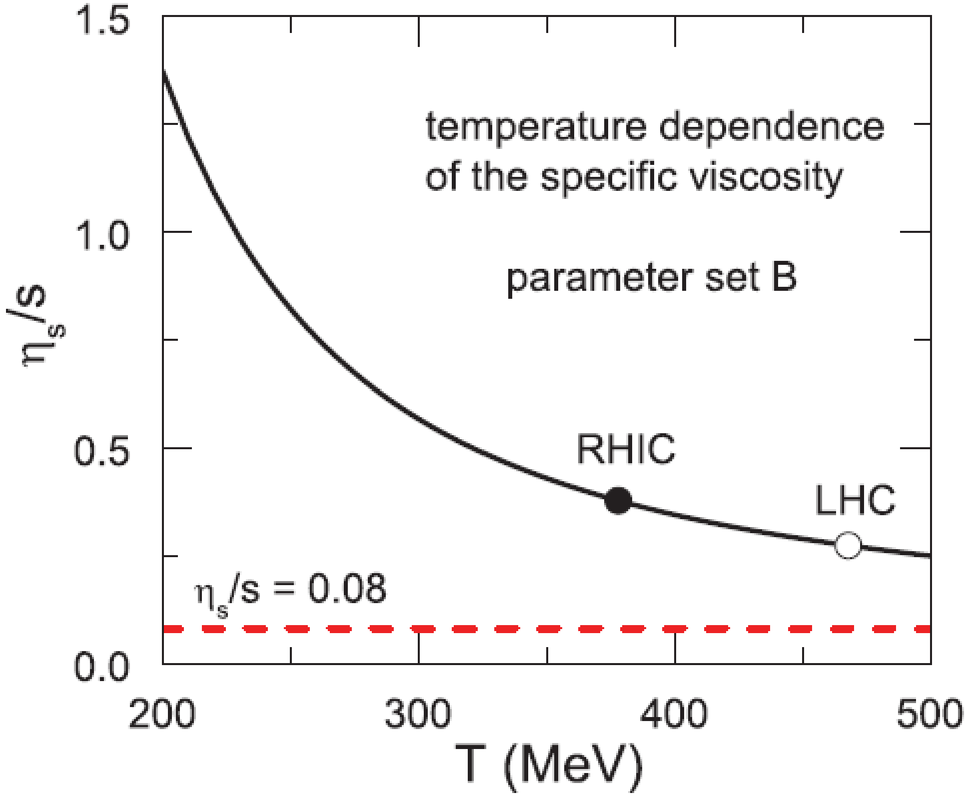
$$\eta_s = 4\langle p\rangle/(15\sigma_{\rm tr})$$

$$\sigma_{\rm tr} = \int dt d\sigma/dt(1-\cos^2\theta)$$

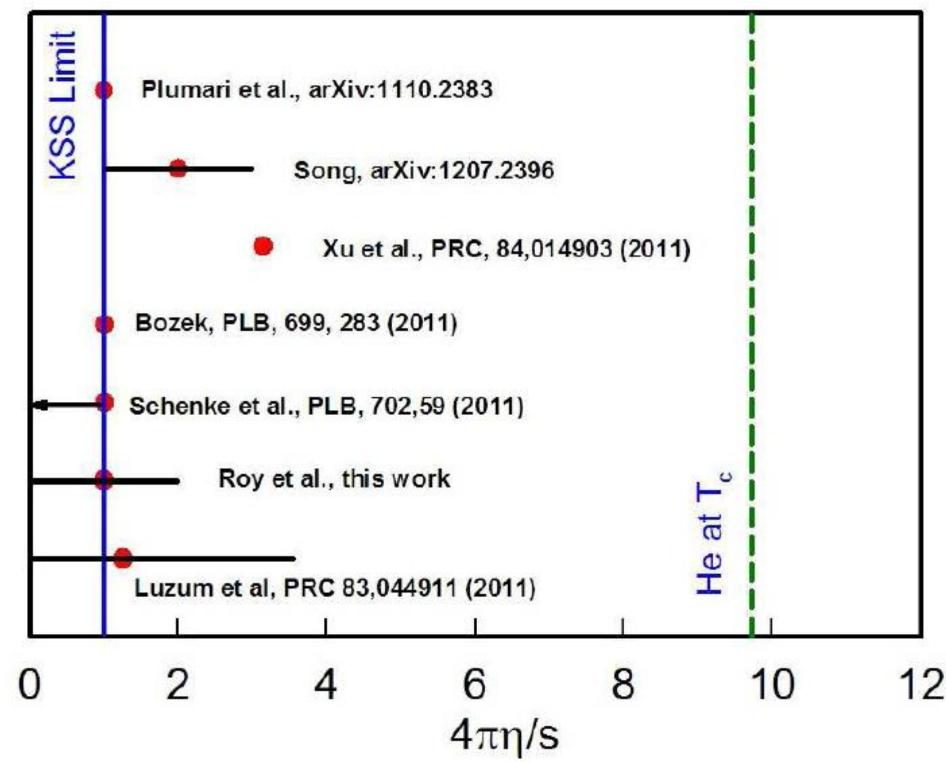
$$\eta_s/s \approx \frac{3\pi}{40\alpha_s^2}\frac{1}{\left(9+\frac{\mu^2}{T^2}\right)\ln\left(\frac{18+\mu^2/T^2}{\mu^2/T^2}\right)-18}$$

Constant dσ/dt rather than constant η/s

η/s at LHC

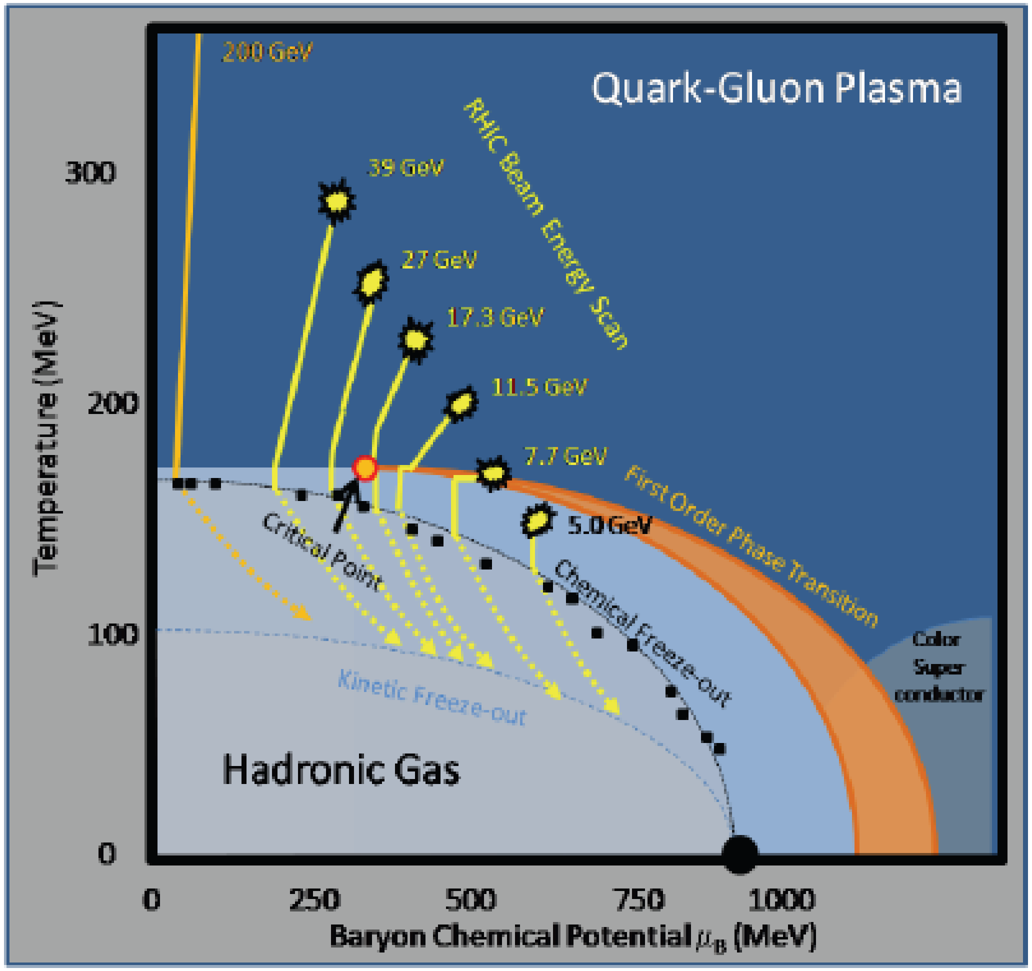


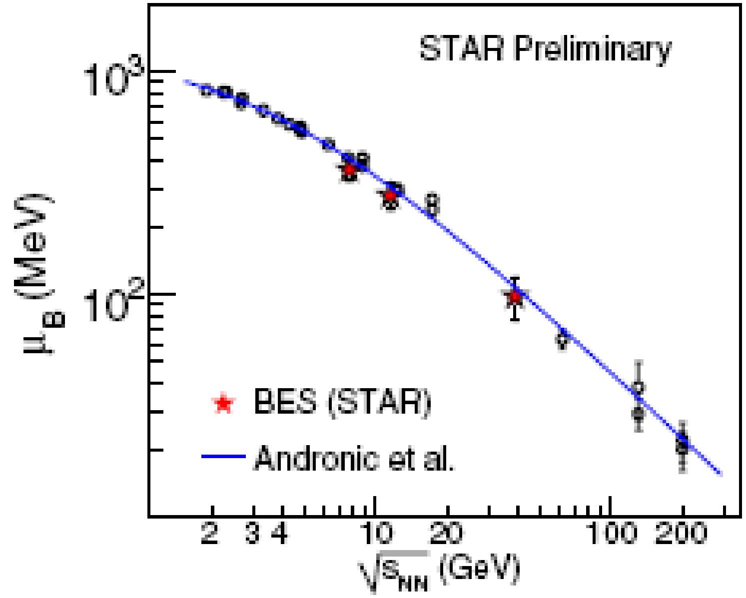
J. Xu and C. M. Ko, Phys. Rev. C 84, 014903 (2011)

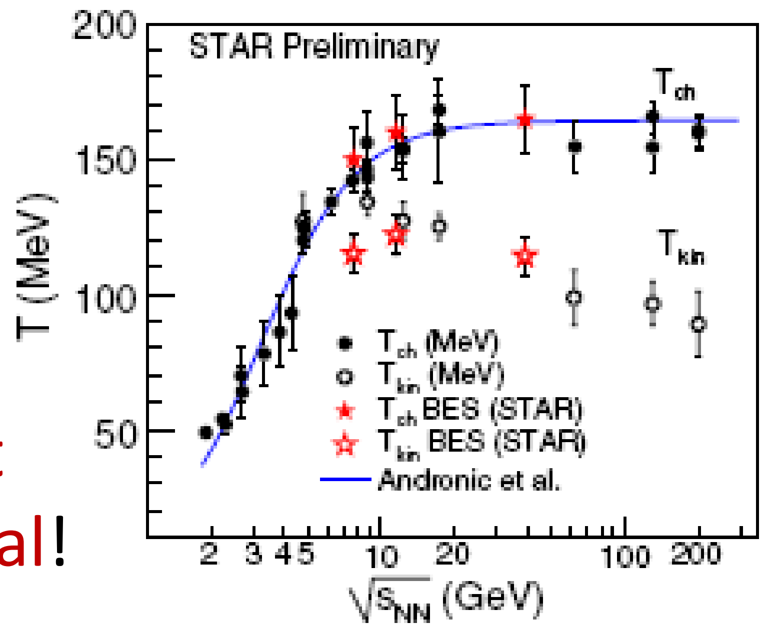


V. Roy *et al.*, arXiv: 1210.1711 [nucl-th]

Beam-energy scan program

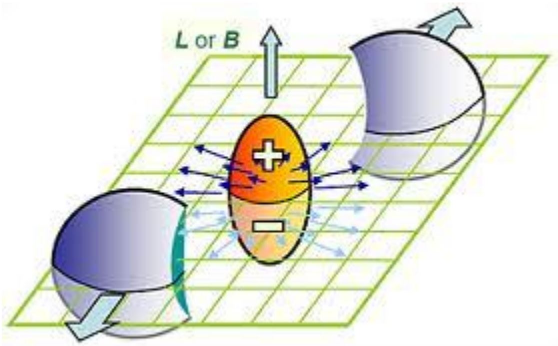


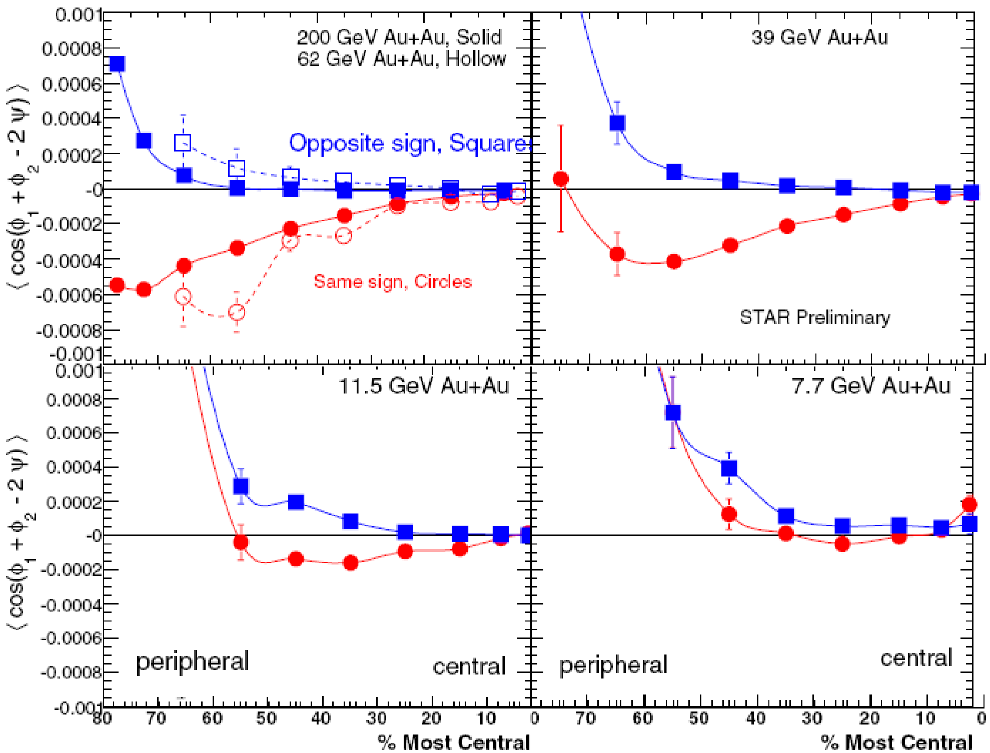




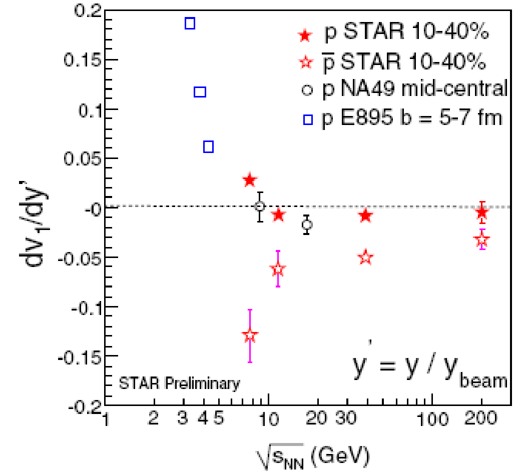
Search for signals of critical point at finite baryon chemical potential!

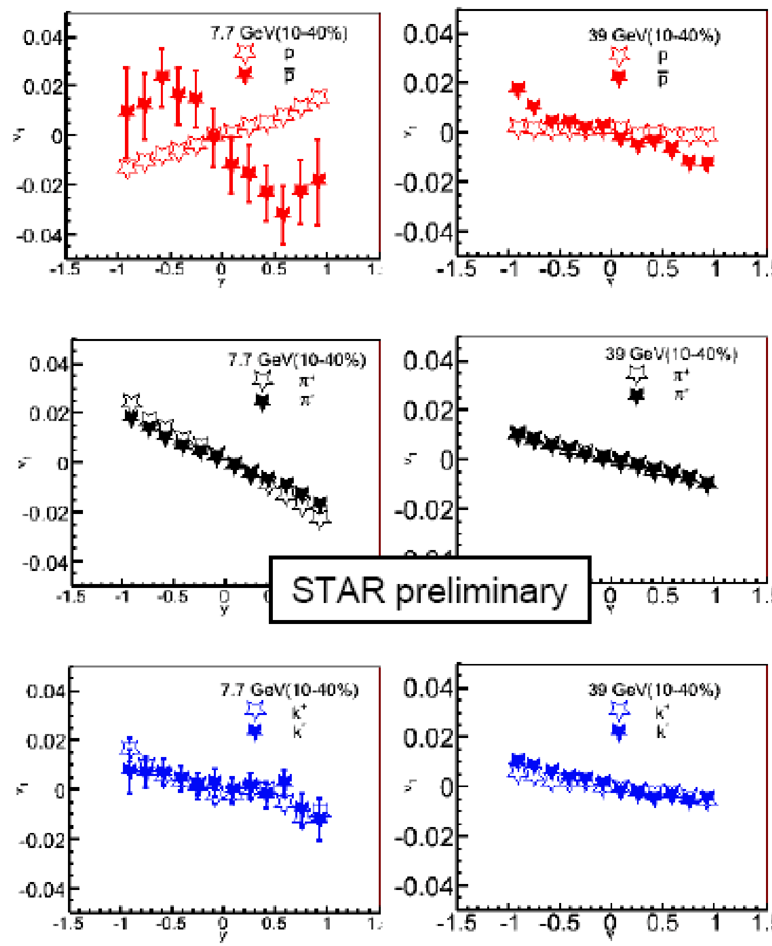
Chiral magnetic effect and charge separation





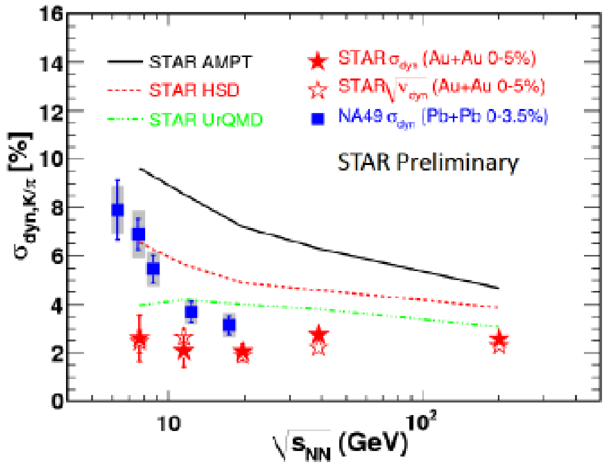
Direct flows of proton and antiproton

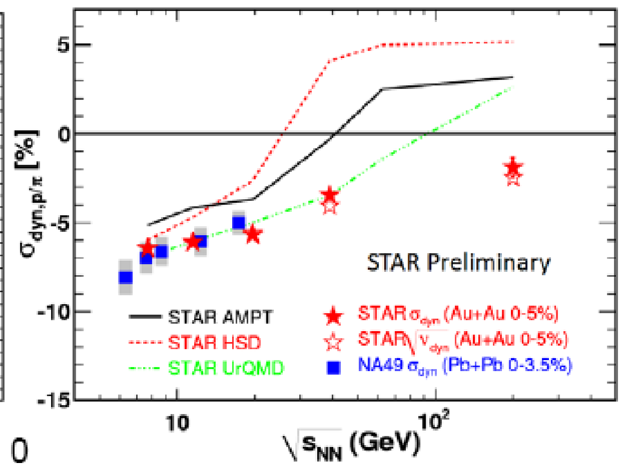




K/π and p/π ratio fluctuation

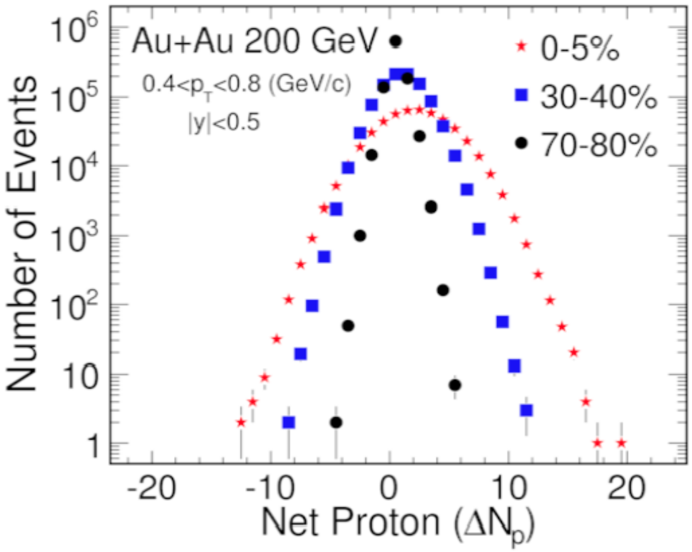
$$\sigma_{\rm dyn} = {\rm sign}\left(\sigma^2_{\rm data} - \sigma^2_{\rm mixed}\right)\sqrt{\left|\sigma^2_{\rm data} - \sigma^2_{\rm mixed}\right|}$$





0

Net proton number fluctuation

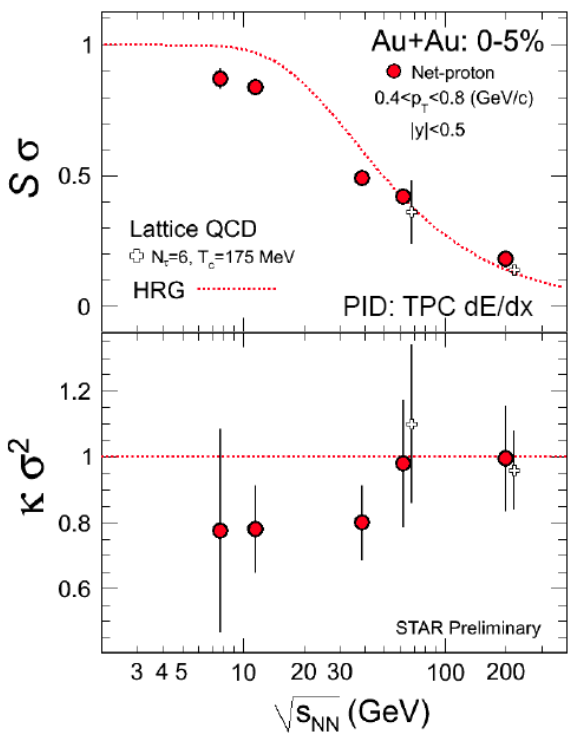


Mean: $M = \langle N \rangle$

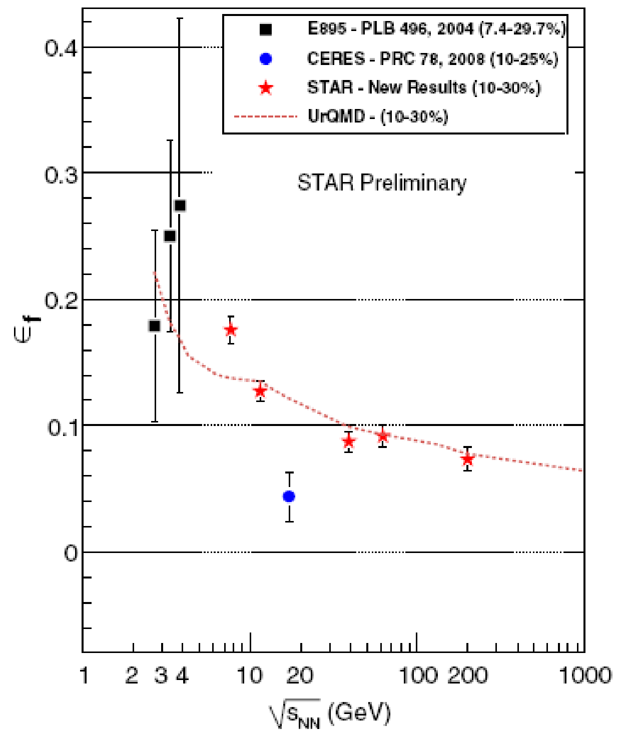
Sigma: $\sigma = \sqrt{\langle (N - \langle N \rangle)^2 \rangle}$

Skewness: $s = \dfrac{\langle (N - \langle N \rangle)^3 \rangle}{\sigma^3}$

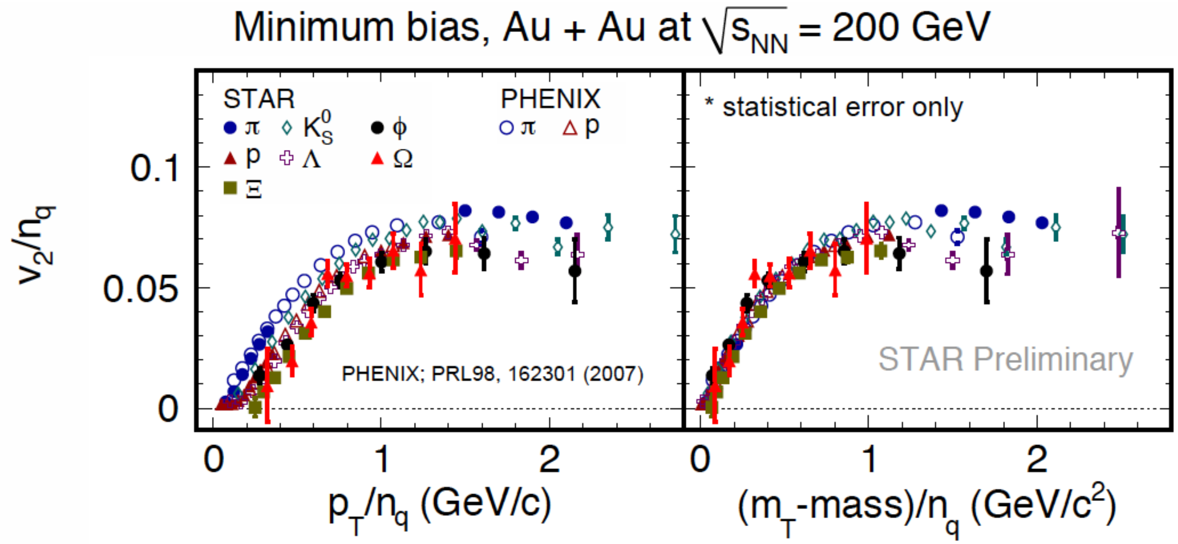
Kurtosis: $\kappa = \dfrac{\langle (N - \langle N \rangle)^4 \rangle}{\sigma^4} -$



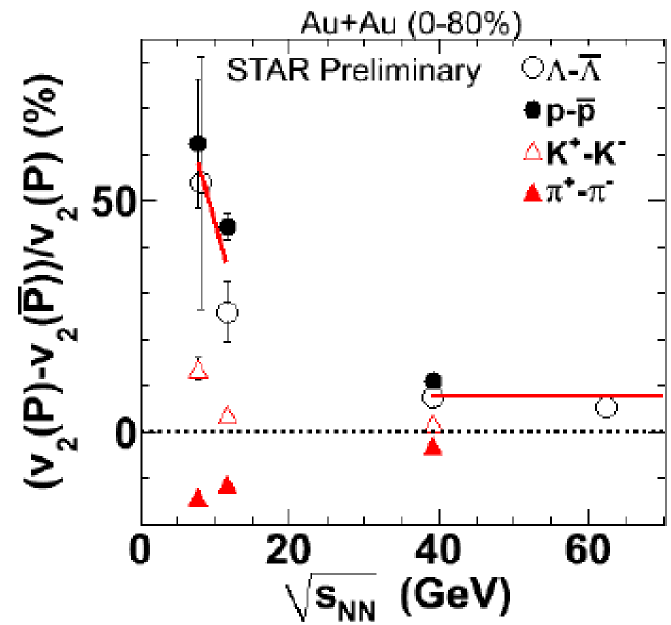
Freeze-out eccentricity (HBT)

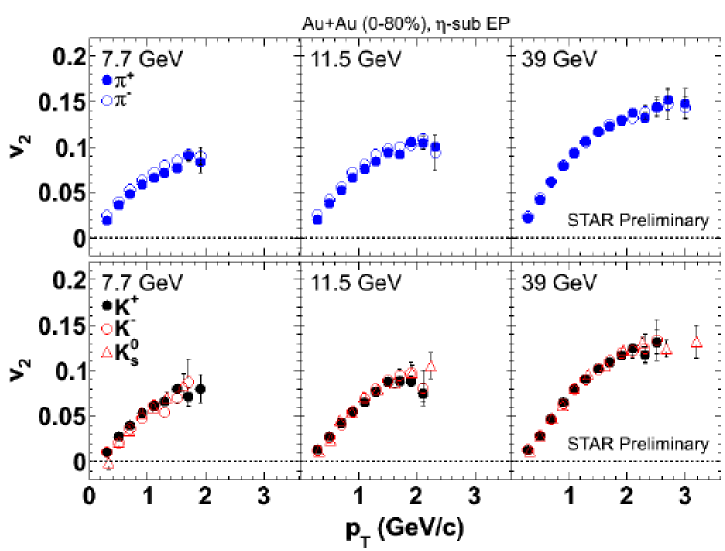


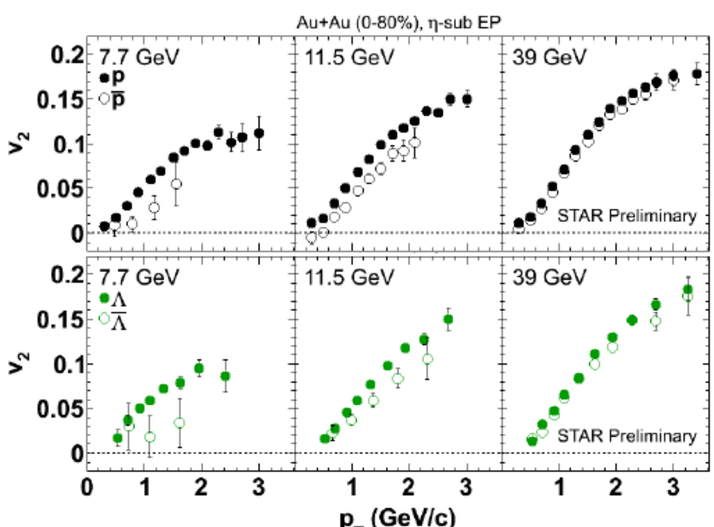
Break down of NCQ scaling



$$v_2^{meson}(p_T) = 2v_2^{quark}(p_T/2) \qquad v_2^{baryon}(p_T) = 3v_2^{quark}(p_T/3)$$







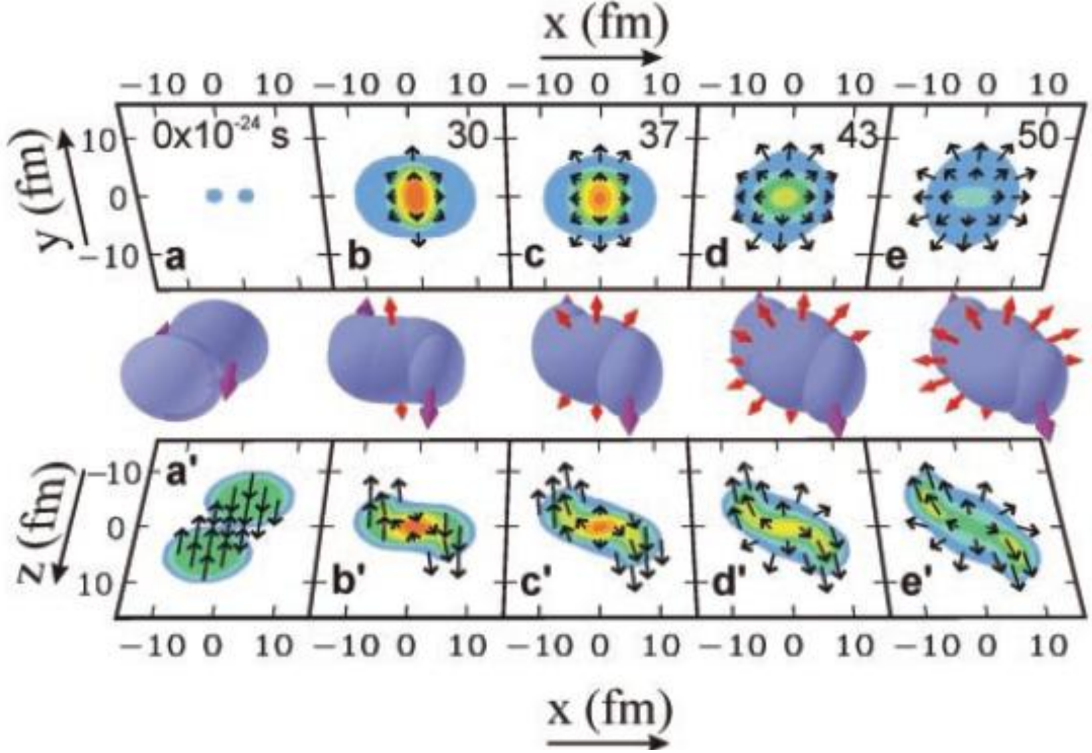
$$v_2(\pi^+) < v_2(\pi^-)$$

$$v_2(K^+) > v_2(K^-)$$

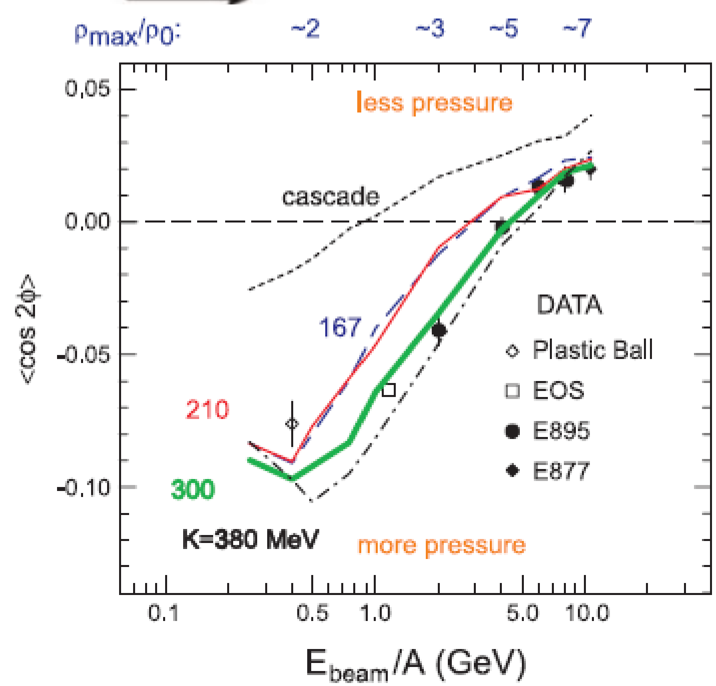
$$v_2(p) > v_2(\bar{p})$$

$$v_2(\Lambda) > v_2(\bar{\Lambda})$$

Effects of hadronic potentials on the elliptic flow at SIS energies:

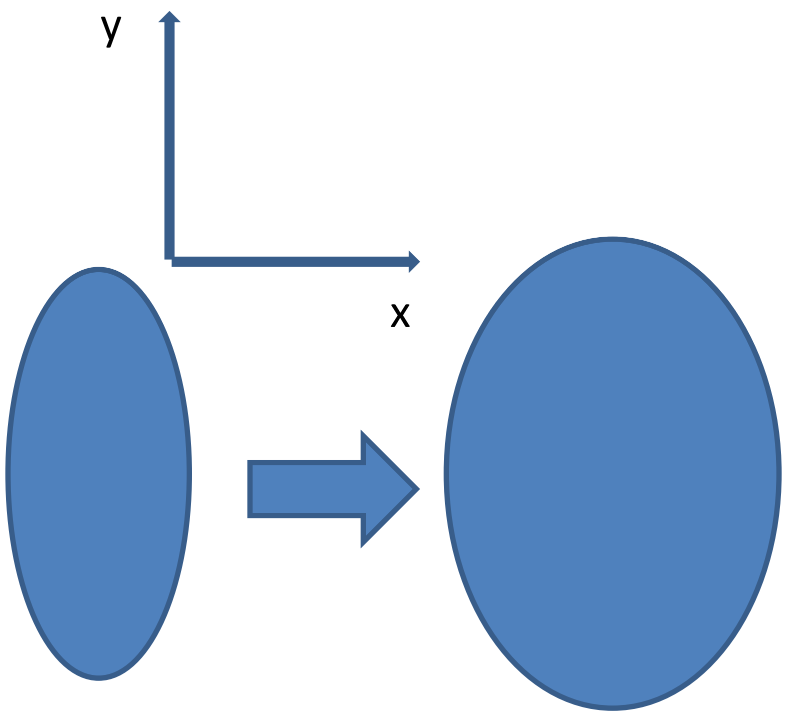


<cos2φ>. More repulsive, higher-pressure EOSs with larger values of K provide more negative values for <cos2φ> at incident energies below 5 GeV per nucleon, reflecting a faster expansion and more blocking by the spectator matter while it is present.



P. Danielewicz, R. Lacey, and W. G. Lynch, Science (2002).

Effects of hadronic potentials at higher energies: no blocking



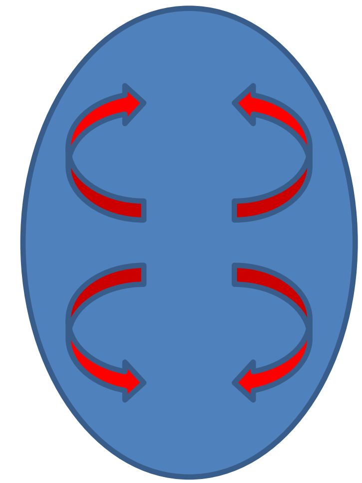
partonic phase

$\varepsilon_2 > 0$

hadronic phase

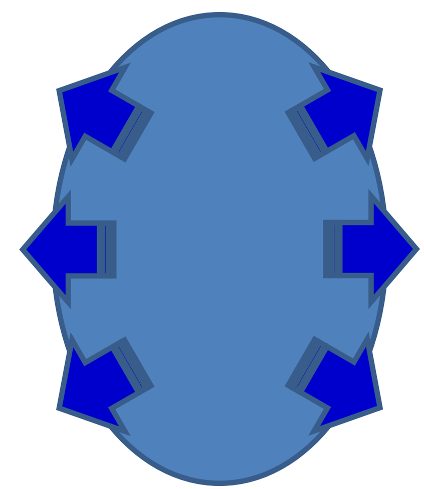
$\varepsilon_2 > 0$

Particles with attractive potentials are more likely to be trapped in the system



v_2 decrease

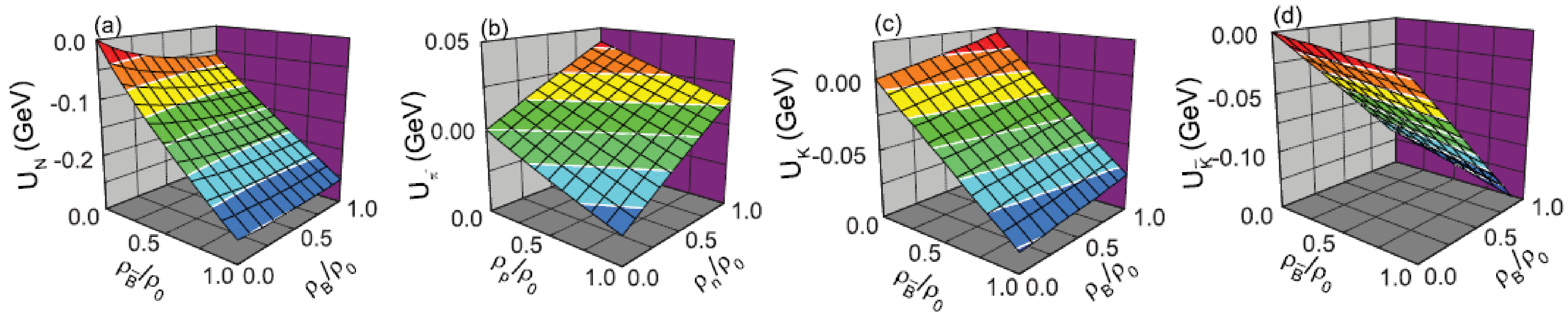
Particles with repulsive potentials are more likely to leave the system



v_2 increase

And …

Hadronic phase becomes more important at lower collision energies



G. Q. Li, C. M. Ko, X. S. Fang, and Y. M. Zheng, Phys. Rev. C (1994)

N. Kaiser and W. Weise, Phys. Lett. B (2001)

G. Q. Li, C. H. Lee, and G. E. Brown, Phys. Rev. Lett., (1997); Nucl. Phys. A (1997)

In baryon-rich and neutron-rich matter:

- Baryon potential: weakly attractive
- Antibaryon potential: deeply attractive
- K^+ potential: weakly repulsive
- K^- potential: deeply attractive
- π^+ potential: weakly attractive
- π^- potential: weakly repulsive

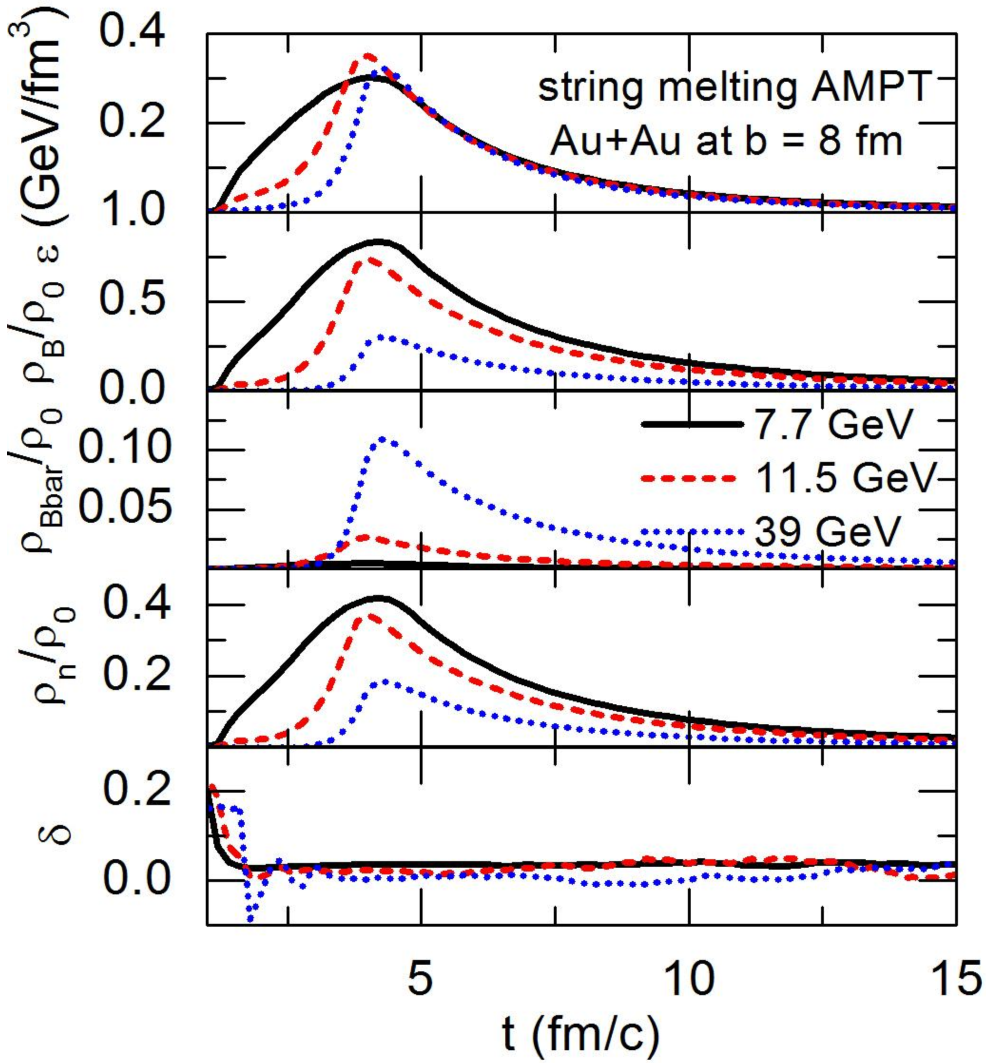
Vector potential changes sign for antiparticles! (e^+e^- exchange γ)

Turn on hadronic mean-field potential in ART in AMPT!

$$T = T_{lim}\frac{1}{1+\exp(2.60-\ln(\sqrt{s_{NN}(\mathrm{GeV})})/0.45)}, \quad \mu_b[\mathrm{MeV}] = \frac{1303}{1+0.286\sqrt{s_{NN}(\mathrm{GeV})}}$$

with the "limiting" temperature T_{lim}=164 MeV

A. Andronica, P. Braun-Munzingera, and J. Stachel, Nucl. Phys. A (2010)



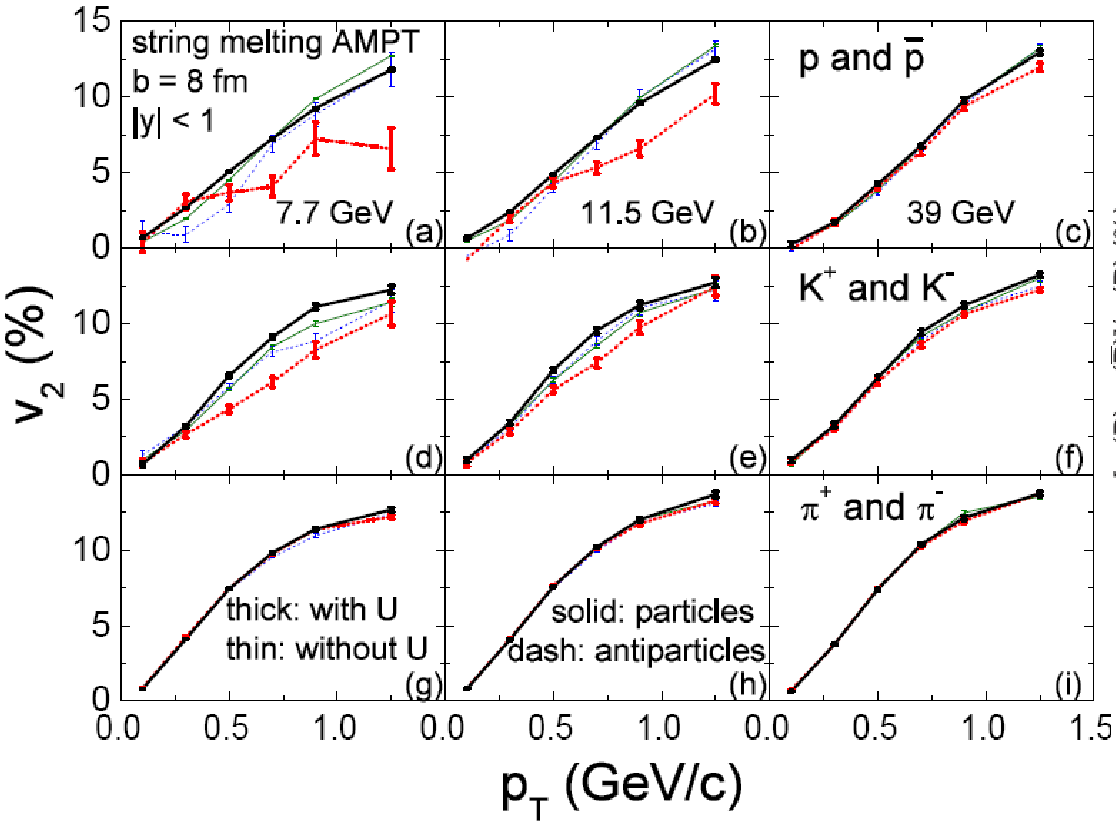
$S_{NN}^{1/2}$(GeV)	**7.7**	**11.5**	**39**
σ (mb)	3	6	10
μ (MeV)	407	304	107
T (MeV)	143	155	163
ε_c (GeV)	0.30	0.35	0.34

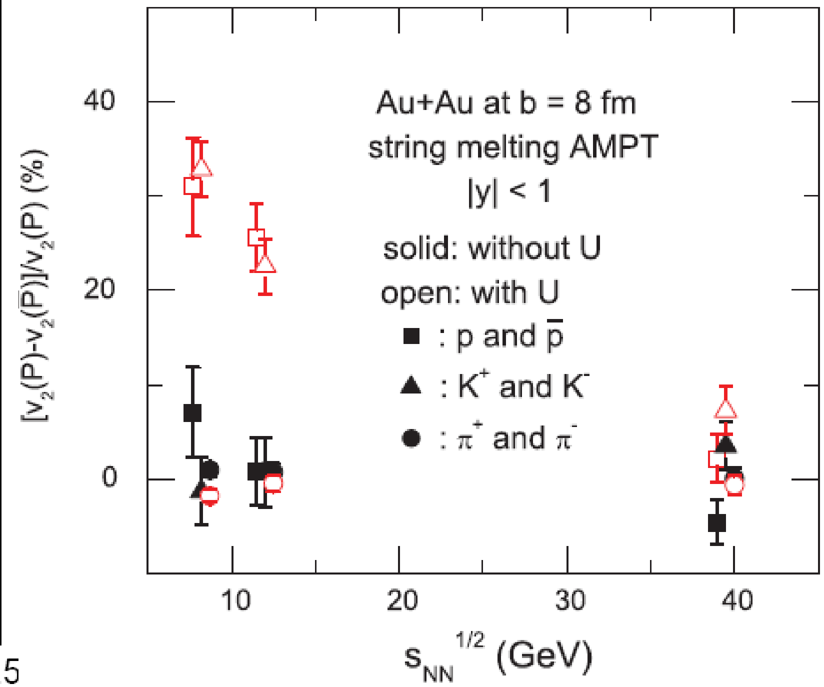
Adjust the life time of the partonic phase.

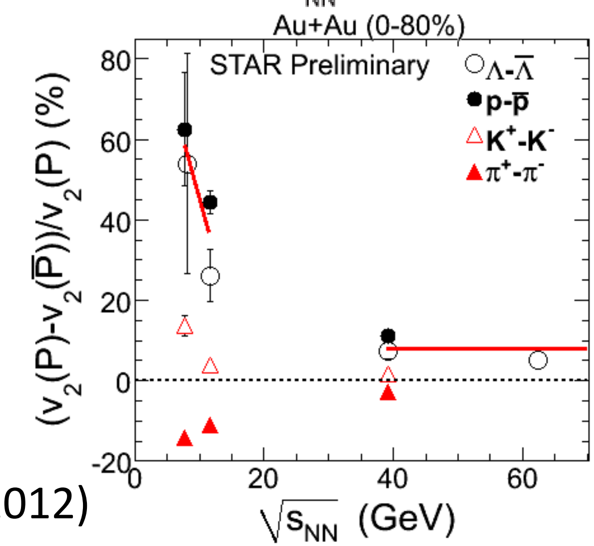
Maximum energy densities are fitted to the values from a statistical model.

(N, Δ, Y, π, K, ρ, ω, … and their antiparticles)

Effects on the elliptic flows







Qualitatively consistent

proton and antiproton: underestimate

K^+ and K^-: overestimate

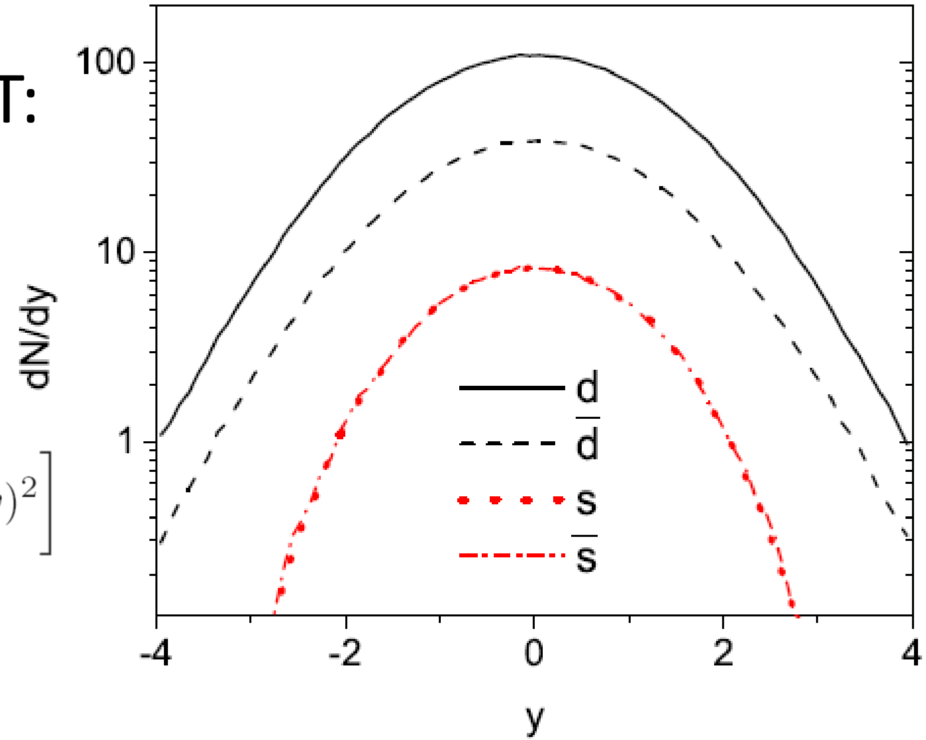
π^+ and π^-: underestimate

J. Xu, L. W. Chen, C. M. Ko, and Z. W. Lin, PRC 85, 041901(R) (2012)

But how about the partonic potential?

From initial condition of AMPT:

A baryon-rich quark system



A three-flavour NJL model:

$$\mathcal{L} = \bar{\psi}(i\not\partial - M)\psi + \frac{G}{2}\sum_{a=0}^{8}\left[(\bar{\psi}\lambda^a\psi)^2 + (\bar{\psi}i\gamma_5\lambda^a\psi)^2\right]$$
$$+ \sum_{a=0}^{8}\left[\frac{G_V}{2}(\bar{\psi}\gamma_\mu\lambda^a\psi)^2 + \frac{G_A}{2}(\bar{\psi}\gamma_\mu\gamma_5\lambda^a\psi)^2\right]$$
$$- K\left[\det_f\left(\bar{\psi}(1+\gamma_5)\psi\right) + \det_f\left(\bar{\psi}(1-\gamma_5)\psi\right)\right]$$

$$G_V = G_A = G/2$$

$$H = \sqrt{M^{*2} + p^{*2}} \pm g_V \rho^0$$

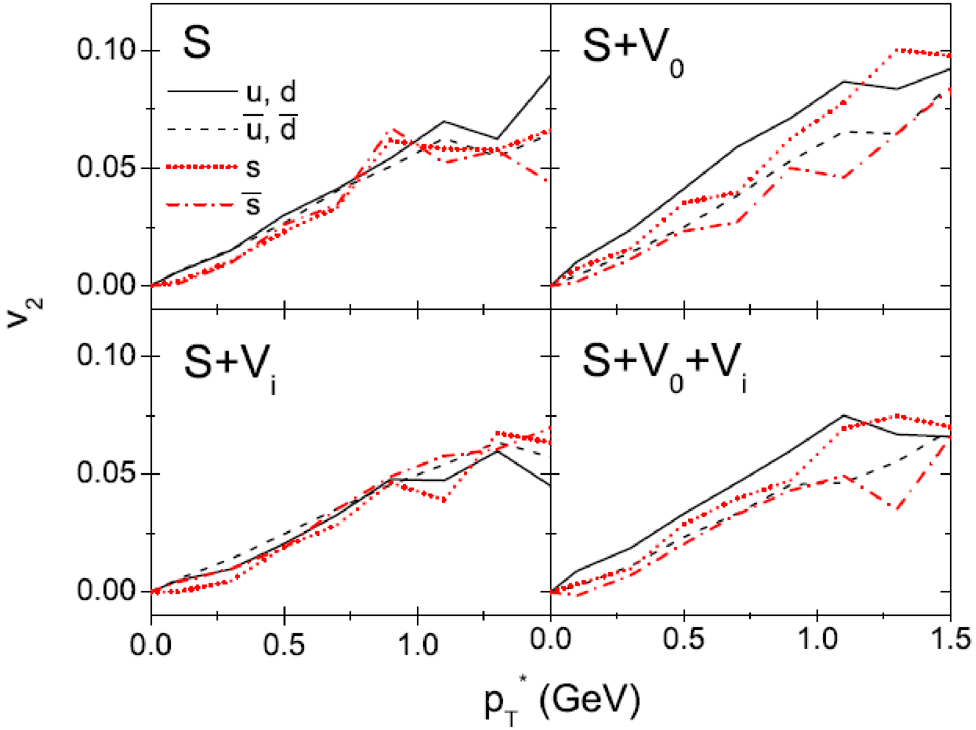
Vector potential changes sign for antiquark!

$$M_u^* = m_u - 2G\langle\bar{u}u\rangle + 2K\langle\bar{d}d\rangle\langle\bar{s}s\rangle$$
$$M_d^* = m_d - 2G\langle\bar{d}d\rangle + 2K\langle\bar{s}s\rangle\langle\bar{u}u\rangle$$
$$M_s^* = m_s - 2G\langle\bar{s}s\rangle + 2K\langle\bar{u}u\rangle\langle\bar{d}d\rangle$$

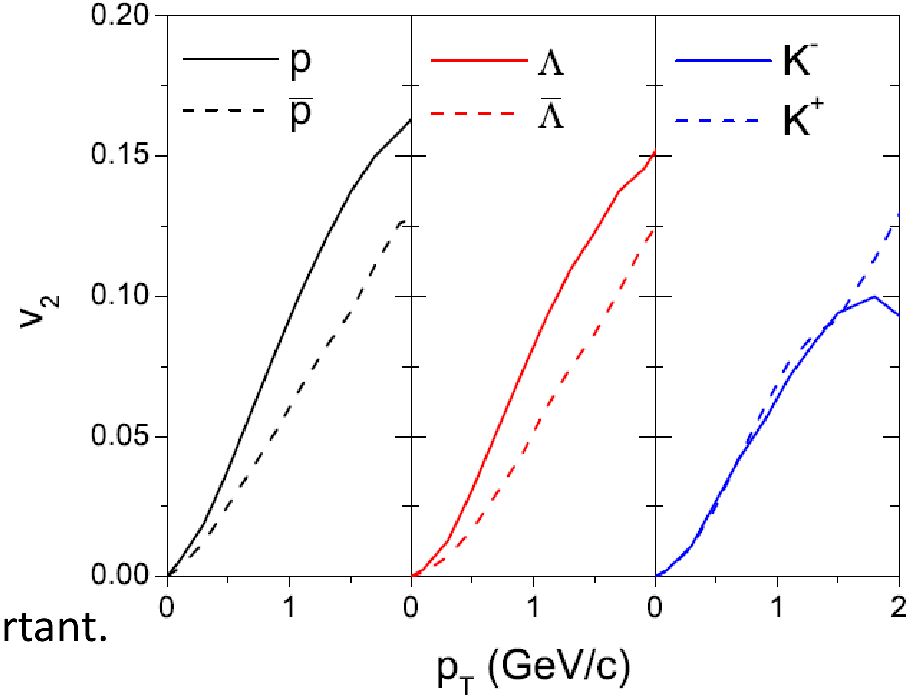
$$\mathbf{p}^* = \mathbf{p} \mp g_V \boldsymbol{\rho}$$

$$g_V \equiv (2/3)G_V$$

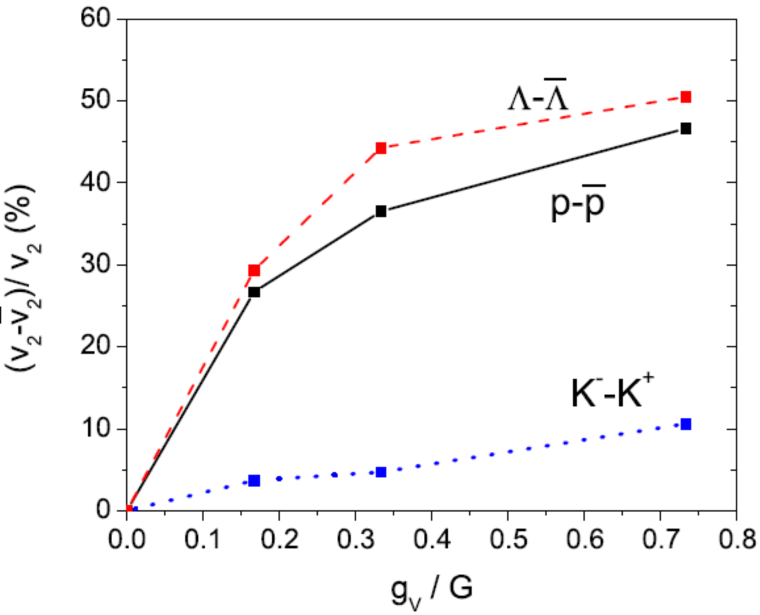
Coalescence from a Wigner function approach



Time component of vector potential is most important.



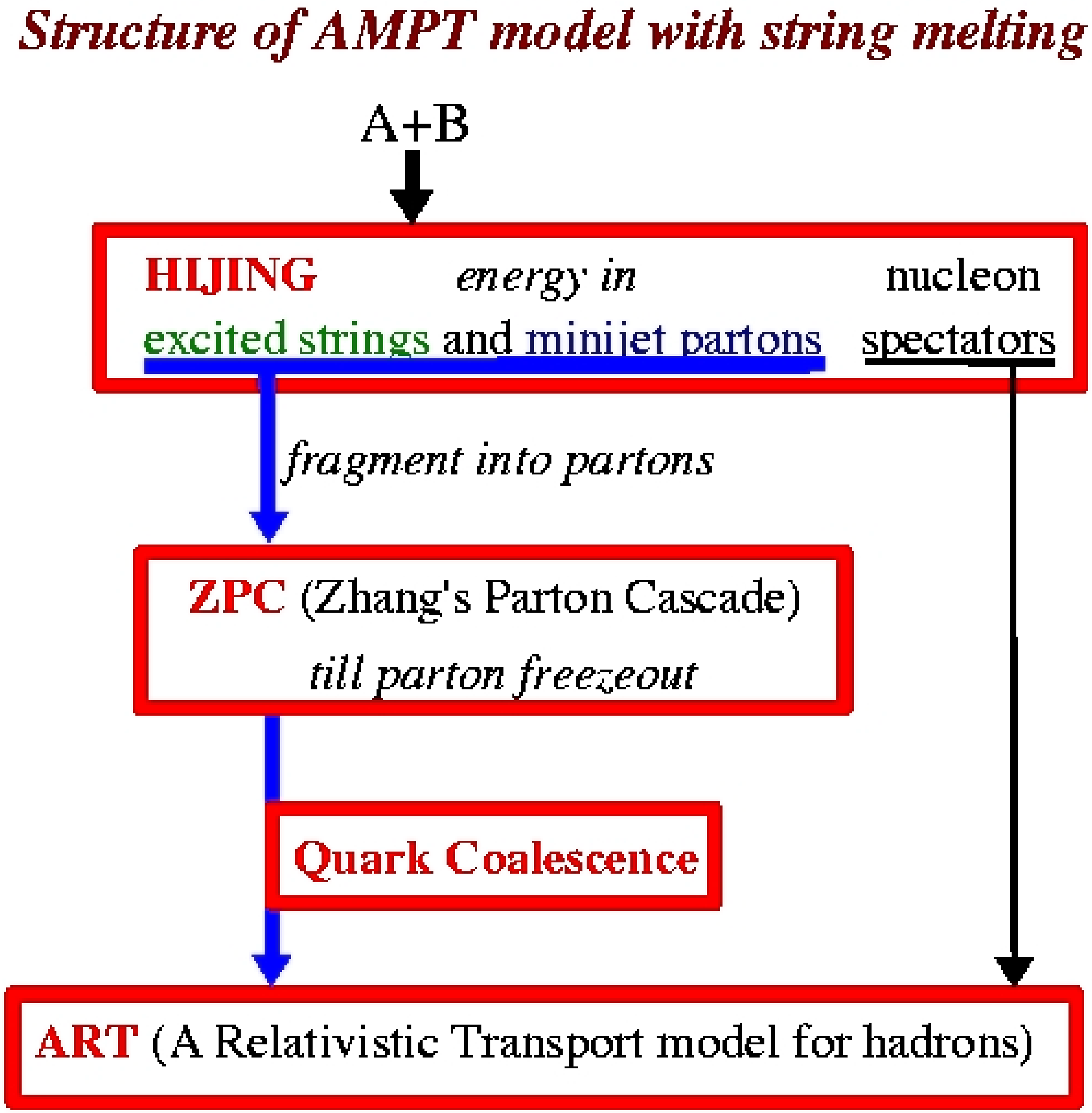
T. Song, *et al.*, arXiv: 1211.5511



v_2 splitting is sensitive to g_v.

The existence and location of the QCD critical point is sensitive to g_v!

N. M. Bratovic, T. Hatsuda, and W. Weise, arXiv: 1204.3788



What if we use default version?

<= Initial condition

<= Partonic phase

(what if replace it with NJL transport model)

<= Hadronic phase:

(turn on potentials)

Screening effects on antiparticle annihilation?

A transport model suitable for BES energies!

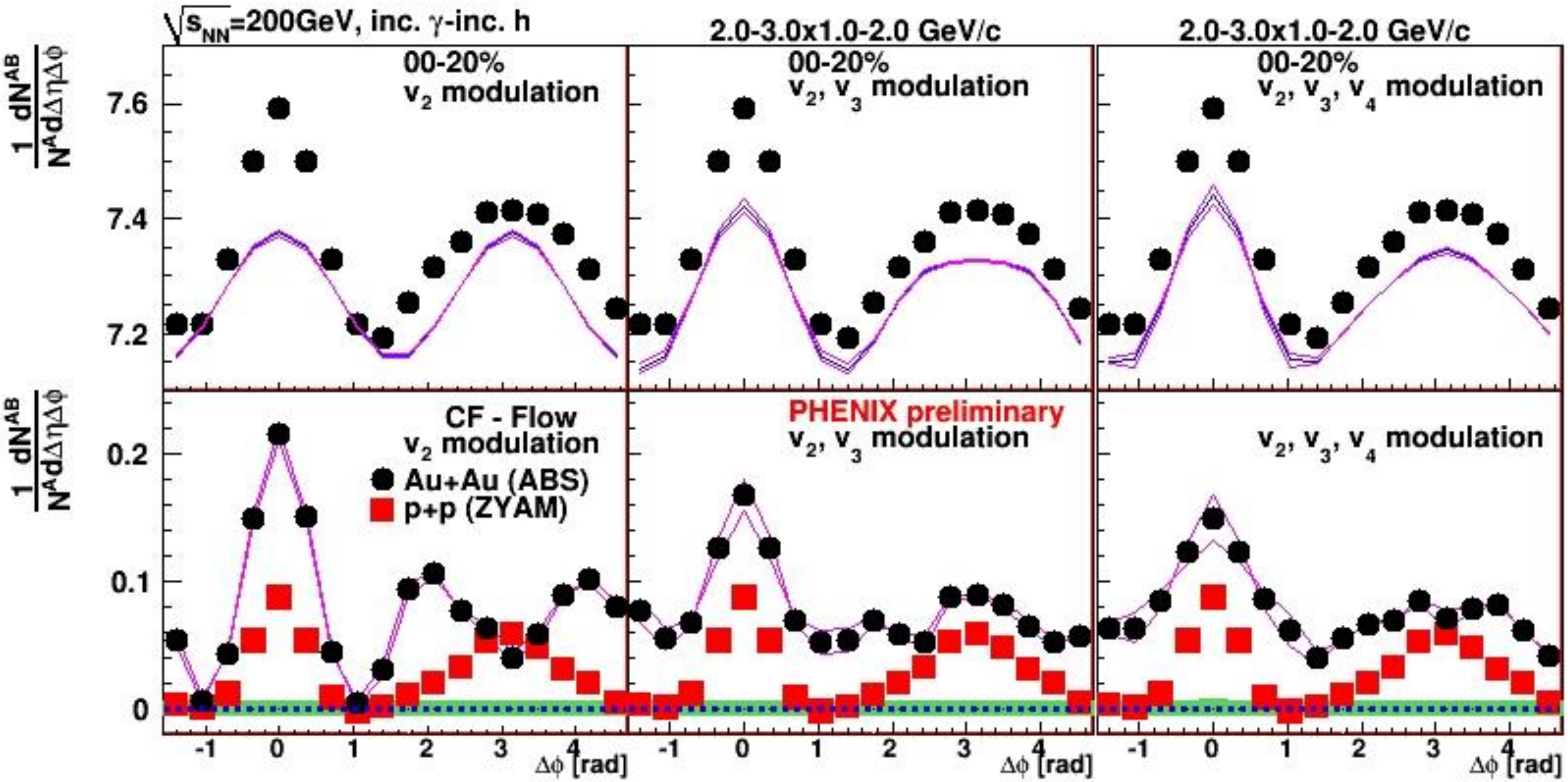
Constrain g_v ...

Thank you!

xujun@sinap.ac.cn

Jet shape with higher v_n modulated background subtraction

200GeV Au+Au
0-20%, inc. γ-had.



- When v_3 modulation is included, the double-peak structure in the away side disappears.